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TDA-RCA Capsule Pipeline Project

Phase 1 Report

Part 1

edited by
Erik J. Jensen

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Alberta
RESEARCH

TDA-RCA CAPSULE PIPELINE PROJECT

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SUMMARY

SUMMARY

The 3-year TDA-RCA Capsule Pipeline project was launched January 1, 1971. Its primary purposes are to analyze the hydrodynamics of capsule pipelining and to produce reliable design equations based on experimental results obtained in pipelines of varying diameters.

A University support program in aid of graduate studies related to capsule pipelining is also included in the project. Two grants totalling $36,000 have been awarded; one to the University of Alberta and one to the University of British Columbia.

The project is managed and executed by the Research Council of Alberta (RCA). The total budget is $850,000, of which the Transportation Development Agency (TDA) contributes $535,000 and the RCA $315,000.

An Advisory Committee composed of members from the RCA and the Solids Pipeline Research and Development Association (SPRDA), and chaired by the TDA liaison officer, has been established and provides guidance to the project.

The contract calls for bi-monthly progress reports which form a continuous log of the project. The TDA-RCA agreement also stipulates the submission of three major reports. The present Phase I report covers the period from the inception of the project to April, 1972, i.e. the construction and initial data-taking period.

The report comprises two parts. Part 1 describes the activities during the period under review while Part 2 contains drawings of the pipelines, computer programs and other documentation.

In Part 1 a review of the analytical work is contained in Chapter II. Chapter III contains a report on an analytical approach and a theory different from the theory previously pursued by the RCA. A comprehensive report on this work has been submitted in a separate volume.

The negotiations that concluded in the awarding of two University grants are detailed in Chapter IV which also contains particulars on these graduate studies.

The University of Alberta study is concerned with statistical model building as applied to capsule pipelining while the University of British Columbia study deals with eccentric laminar couette flow in a cylindrical capsule pipeline. Both programs are to be considered studies related to the analytical work. Continuous liaison is maintained with the grantees through frequent meetings.

Following initial data taking and subsequent analysis of this data a broad outline of an experimental program for the 4 and 10 inch pipelines then in operation was drawn up. This program is described in Chapter V.

The 4 inch pipeline with attendant instrumentation and computer facilities was completed in October, 1971. It is described in detail in Chapter VI.

The 10 inch pipeline facility located on leased land on the outskirts of Edmonton was ready for data taking in February, 1972. A detailed description of this facility is contained in Chapter VII.

A good start has been made on the project. In spite of some delays at the outset there appears to be adequate time to complete the project.

CHAPTER I

INTRODUCTION

CHAPTER I

INTRODUCTION

On the 29th of March, 1971, a contract was signed between the Canadian Ministry of Transport, represented by the Transportation Development Agency (TDA) and the Research Council of Alberta (RCA), stipulating a three-year research program, beginning January 1, 1971, on capsule pipelining with the following purpose:

> "To produce experimental data from a series of test lines, one of which should be sufficiently large to enable meaningful measurements to be made of capsule pressure distributions, wall clearances, attitudes, etc. and to be representative in size of a practical line.
>
> "To develop analytical means of predicting the behaviour of trains of capsules of various configurations in liquid carriers. At least one method should be thoroughly explored by the team conducting the overall project. Alternative analytical approaches should be investigated and promising lines pursued by forming associations and exchanging information with other experts, by making grants available to post-graduate students from university centres and by additional in-house studies."

Up to 10% of the allocated funds can be used in aid of university research programs for the purpose of broadening the Canadian expertise in capsule pipelining.

Consequently a grant has been made to the University of Alberta, Department of Chemical Engineering. A graduate student, Mr. H. Singh, under the direction of Dr. D. Quon, is working on his Ph.D. degree as a result. Further details on this work are provided in Chapter IV.

Another grant has been awarded to the University of British Columbia, Department of Chemical Engineering. Dr. N. Epstein is in charge of projects made possible with this aid. Further details are contained in Chapter IV.

The project is financed jointly by the Ministry of Transport through the Transportation Development Agency, which contributes a total of $535,000, and the Research Council of Alberta which contributes services estimated in the Federal Treasury Board submission at $315,000, for a total of $850,000.

Outside help has been used where required. Dr. V.K. Garg was retained as a consultant from June 1 to August 31, 1971. Other consultants have been retained on a contractual basis during the construction phase, notably Green, Michaels and Associates Ltd., Consulting Electronic Engineers.

Much valuable assistance has been donated by the Transportation Development Agency and other Federal departments and agencies as well as by the Solids Pipeline Research and Development Association and its member companies.

An advisory committee is called for in the Statement of Requirements. The committee, which at the time of reporting has met twice, has the following membership:

Mr. J.G. Bruce, Secretary-Treasurer, Solids Pipeline Research and Development Association (SPRDA)
Mr. R. Cushing, Northern Natural Gas Company, Omaha, Nebraska
Mr. P. L. Eggleton, TDA
Mr. E. J. Jensen, RCA
Mr. R. A. King, ShelPac, Toronto
Dr. E. J. Wiggins, RCA

The TDA Liaison Officer to the project is:

Mr. Peter L. Eggleton, Chief, Surface Transport Projects

The RCA appointed Project Director is:

Mr. Erik J. Jensen, Head, Engineering Division.

Other Research Council of Alberta staff members working on the project include:

Mr. P. Afaganis
Dr. R.A.S. Brown
Mr. H. Dalpe
Mr. H. S. Ellis
Mr. G. E. Johanson
Mr. Jan Kruyer
Mr. E. Parranto
Mr. A. A. Roehl
Mr. L. White
Mr. K. Wourms

The contract also stipulates that bi-monthly reports must be submitted. This has been done as required, and these reports are intended to form a continuous log of the project.

Phase reports are required as follows:

"Phase I

a) Technical report on design and construction of test facilities.
b) Test plan for Phase II with justifications.
c) Report on analytical work.
d) Proposal for any research grants or consultant activity from project funds.

Phase II

a) Report on additional analytical solutions obtained.
b) Interim report on test results.

Phase III

a) Final report representing major experimental results viewed against analytical solutions plus conclusions and implications of the project as a whole".

The present report is the Phase I report and covers activities from January, 1971 to April, 1972 in areas indicated in the List of Contents. It consists of two parts. Part 1 is a report on the activities during the period under review while Part 2 contains drawings of the pipelines, computer programs and other documentation.

Work on the all-important hydrodynamic analysis was begun as soon as the project was initiated and does in reality constitute a continuation of the work that began shortly after the concept of capsule pipelining was defined by Research Council of Alberta staff members about 1959. The results of this work prior to the beginning of the project are reflected in the numerous publications issued over the years. The project calls for:

> "The development of analytical means of predicting the behaviour of trains of capsules of various configurations in liquid carriers. At least one method should be thoroughly explored.... Alternative analytical approaches should be investigated ...."

An analytical approach different from that employed earlier by the Research Council of Alberta team has been pursued and reported in the volume entitled:

> Jan Kruyer and V.K. Garg: Pressure and Couette Flow in a Capsule-Pipeline System - Theory and Experiment.

A condensed version of this report, presented as a paper at the Hydrotransport 2 Conference is contained in Chapter III.

Another analytical approach is being pursued by Dr. N. Epstein of the University of British Columbia as part of the previously-mentioned university support program and is outlined in Chapter IV.

The main analytical work, on which the success of the project in large measure depends, is carried out by members of the Research Council of Alberta team. Details of the guiding principles are included in Chapter II.

It might be in order to restate the rationale behind the analytical approach at this point. Observers of the Research Council of Alberta hydrodynamic work have from time to time stated that a fundamental description in terms of classical physics based on experimentally verifiable facts would be the only satisfactory outcome of the analysis. No hydrodynamicist would deny this. Over ten years of work in this field has, however, made it abundantly clear that this desirable goal is unattainable. More than 100 years of theoretical work with fluid pipelines has failed to produce a description of this nature for these systems. The complications that the introduction of capsules into a liquid-filled pipeline creates are such that the prospect of a solution in purely scientific terms is even more remote.

This does not mean that this goal should be lost sight of, but it does mean that an analysis which has to produce results useful to the design engineer in a limited time has to resort to a semi-empirical solution that accounts for as many parameters and variables as accurately as possible.

This is what is being done in this case and it is made possible only because of the availability of the computer. The desire to make this numerical solution as reliable as possible explains why it is necessary to gather the great amount of experimental data. An outline of the experimental program is presented in Chapter V.

The experimental part of the project included the construction of 5 pipelines. The anticipated building time as set out in the time schedule contained in the Work Statement submitted to the Transportation Development Agency was 9 months. It has not been possible to maintain this schedule. The 4 inch facility was read for data-taking in October 1971. The 10 inch pipeline was completed at the same time except for instrumentation and computerization. This line was ready for data-taking in February 1972. The remaining 3 lines are under construction. The $\frac{1}{2}$ inch line is expected to be operational in December 1972, and the remaining 2 lines will be completed as required. This change of schedule from the original plans was necessitated because the same set of instruments and electronic equipment must be used on all the laboratory lines. They, therefore, have to be operated consecutively and the changed schedule means better utilization of available equipment and staff.

Details of design and construction of the 4 and 10 inch pipelines with attendant experimental programs are presented in Chapters VI and VII respectively.

In the Statement of Requirements it is stated that:

> "The project should lead to a point where a meaningful decision can be taken on the feasibility of a large-scale demonstration line or of an actual application."

This is interpreted to mean that a proposal for a continuation of the project in the form of a demonstration line or a commercial application should, if possible, be suggested.

One such application appears to present itself in the form of transportation of solid waste. Discussions have been initiated with the Transportation Development Agency and other agencies, and a proposal is under preparation and will be presented at a later date.

It may in conclusion be stated that the project is off to a good start, that the requirements stipulated in the contract have been met, and even though it has been impossible to comply completely with the projected time schedule, there will be ample time to gather the necessary data and to formulate reliable design criteria for capsule pipelining.

CHAPTER II

Review of Analytical Work

CHAPTER II

Review of Analytical Work

A capsule pipeline can be designed hydrodynamically from experimentally-derived correlations of the main parameters and variables of capsule flow. However, a real understanding of the dynamics of capsule flow requires an experimentally-verified analysis of at least the major factors involved. The present account describes the progress towards such an analysis.

The flow of infinitely long concentric cylindrical capsules was analyzed by Charles in 1962 (1) for both laminar and turbulent flow, with Kennedy (2) suggesting modifications for turbulent flow in 1966. The pressure and shear forces acting on a cylindrical capsule denser than the liquid were described by Ellis in 1964 (3) when he presented velocity data for such capsules. In 1964 Newton, Redberger and Round (4) analyzed numerically four variables determining free laminar flow of capsules, and this treatment was extended through the use of an expression due to Bentwich, Kelly and Epstein (5),by Kruyer, Redberger and Ellis in 1967 (6). Analytically-derived capsule velocities and the associated pressure gradients were presented for laminar flow in terms of the clearance between the pipe and an infinite cylinder for a wide range of capsule/pipe diameter ratios. The analysis was verified by experimental data from two pipelines of widely different diameter.

An approach which has both commercial and theoretical relevance was adopted by Ellis and Kruyer in 1970 (7). Capsule pressure gradients for a wide range of conditions were correlated on a Fanning-type friction factor-Reynolds number diagram by the use of a velocity compounded of the annuluar liquid and capsule velocities, the "equivalent velocity". This approach is a step towards capsule pipeline design since it provides a relationship between the pressure gradient and the two velocities. However, it does not explicitly involve the capsule density, and this parameter or an equivalent, such as capsule-pipe friction, must be included for a complete relationship. With the same reservations the equivalent velocity approach also leads to an analysis of the relationship between the mean shear stress on the capsule and pipe walls and the bulk (liquid) and capsule velocities. Such an analysis is in preparation (see Progress Report No. 6.1 (b), TDA-RCA project).

The approach of Garg and Round (8) published in 1971 will be described in some detail since it is the basis for a report to the Transportation Development Agency submitted in 1972 (9) and a current paper (10), see chapter VIII, and probably for future work. Garg and Round dealt with the complex problem of an eccentric cylindrical capsule propelled through a pipe by a turbulent liquid by dividing the problem into two parts, considering them separately and finally combining the results. First, the effect of an imposed pressure gradient on a stationary cylinder in the pipe was considered. The turbulent flow of liquid through the annulus (the pressure flow) produces shear forces on the capsule. For a given eccentricity and pressure gradient these can be calculated and represent a thrust on the capsule. In fact, if friction is assumed to be zero, as was done by Garg and Round, a stationary capsule is only a mathematical device, since both the pressure and shear forces would act to accelerate the capsule, and it would not remain stationary. However, one part of the shear forces is calculable in this way.

The other part of the problem, the movement of the capsule, must then be dealt with. The capsule is considered to be pulled through an initially stationary liquid in a pipe at some assumed constant velocity which corresponds to the capsule velocity in the real system at the pressure gradient previously imposed for the static case. The movement of the capsule produces a steady flow of liquid in the annulus through shear - the so-called Couette flow. In this part of the analysis the flow due to the pressure gradient has been ignored, as was the capsule movement in the first part. The shear force on the capsule due to its movement evidently opposes that movement and, in the absence of friction, is the only force to do so. Therefore, if the capsule velocity has been correctly selected to correspond with the pressure gradient, the Couette drag force due to capsule movement will be equal to the known thrust forces due to the pressure flow. Since the Couette shear force has to be calculated numerically it is not possible to set up an equation to solve for the capsule velocity directly; it has to be found by an iterative procedure for each pressure gradient. The correctness of the solution depends on the validity of dividing the problem into two parts, i.e. on the algebraic addition of the shear forces due to

the Couette and pressure flows yielding the net shear force on the capsule. This is known to be true for laminar flow and is assumed to be valid also for turbulent flow.

In this way Garg and Round, making certain assumptions about the velocity profiles in the annulus, produced predictions for the capsule and liquid velocities for different pressure gradients with a given capsule-pipe eccentricity. Though not rigorous like the method of Bentwich et al. (5) for laminar flow, this approach was a valuable contribution to the solution of the turbulent flow problem.

In the summer of 1970 Dr. Garg was retained by the RCA to adapt the computer program of his M.Sc. thesis on which reference 8 is based, to the University of Alberta I.B.M. system and to compare the predictions with data from the RCA 1 1/4 inch copper pipeline. For capsule/pipe diameter ratios of 0.90 and larger, to which the theory is limited, the predictions generally correlated well with the experimental data in the intermediate range of capsule velocity and density, while disagreement between theory and experiment occurred with dense capsules at low velocities and with light capsules at high velocities. These conditions fall outside the limits of the theory, which assumes frictionless flow of the capsules parallel to the pipe wall; the first disparity presents conditions where friction probably cannot be neglected, and the second occurs when the capsules flow at a relatively large angle to the pipe wall. The theory may therefore be considered reasonably well verified within the imposed limitations of frictionless parallel flow of large cylinders. Kruyer and Garg (9 and 10) report complete details of this work. A further program was written by Garg (Appendix AIII in reference 9) to eliminate the restrictions of frictionless flow of the capsule parallel to the pipe wall, but this requires a knowledge of the friction between the capsule and the pipe wall and the angle and clearance between the two, all of which vary with velocity and have eluded experimental determination so far. Kruyer and Garg (9) conclude that "further work will have to be done to make the program more applicable to practical capsule pipeline flow before it can be considered as the theoretical basis for predicting capsule behavior".

Further work is planned on the semi-empirical examination of the capsule and wall shear stresses through momentum transfer theory. These shear stresses are not related directly to the annular velocity since different capsule velocities at the same annular velocity produce different shear stresses. An equivalent velocity based on both annular and capsule velocities must be used for momentum transfer considerations, and progress has been made in relating the capsule and pipe shear stresses to this velocity. This work, like the friction factor-Reynolds number relationship requires the refinement of the equivalent velocity concept. In recent months definitions have been found that give closer friction factor-Reynolds number relationships than that used in (7), and they are more firmly based on theory. Data from the 4 inch and 10 inch pipelines will be used to determine the most satisfactory expression for the equivalent velocity, as well as to investigate the effects of pipe diameter and capsule-pipe friction. The importance of including the latter in any correlation has become increasingly clear (see chapter VI), especially with the marked effect on pressure gradient and velocity of the roughening of the 4 inch diameter plastic pipeline. Although both sets of data, before and after roughening, plot on the same friction factor-Reynolds number curve due to the use of an equivalent velocity, the values of pressure gradient and capsule velocity are very different at the same liquid velocity. The measurement of the coefficient of friction in all pipelines is therefore absolutely essential to a meaningful correlation.

Technical Papers

In addition to the three papers prepared for Hydrotransport 2 (see TDA-RCA Progress Report No. 7), sponsored by the British Hydromechanics Research Association, a paper on the flow of liquid through annuli with stationary cores is planned.

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CHAPTER III

Pressure and Couette Flow in a Capsule-Pipe System

Experimental Verification

by

Jan Kruyer and V. K. Garg

RCA Contribution No. 564
February 1972

CHAPTER III

Pressure and Couette Flow in a Capsule-Pipe System - Experimental Verification

Preface

The TDA-RCA contract requires that: ....."alternative and analytical approaches should be investigated ....."

This has been done by applying the theory developed by Garg and Round to results obtained in a $1\frac{1}{4}$ inch capsule pipeline. The detailed results of this work was reported in the volume Jan Kruyer and V.K. Garg: Pressure and Couette Flow in a Capsule Pipeline System - Theory and Experiment. A condensed version was presented at the Hydrotransport 2 Conference held in England in September, 1972 and is included in this chapter.

Experimental measurements with cylindrical capsules carried through a $1\frac{1}{4}$ inch (32.2 mm) pipeline by water in turbulent flow are compared with the theory developed by Garg and Round for large diameter ratio, frictionless capsules moving parallel to the pipe wall. While in practice capsules do not flow strictly parallel to the pipe wall and are influenced by solid-solid friction there is good agreement between theory and experiment except at high velocities for the low density capsules and at low velocities for the high density capsules.

NOMENCLATURE

A	Area of an incremental section
D	Pipe inside diameter
d	Capsule outside diameter
e	Eccentricity (eqn. 5)
f	Friction factor (eqn. 4)
g_c	Gravitational conversion factor
k	Capsule to pipe diameter ratio
L_c	Length of capsule
L_p	Distance between pipeline pressure taps
n	Integer (eqn. 5)
P	Wetted perimeter of an incremental section
Re	Reynolds number (eqn. 3)
V_{an}	Average annular liquid velocity
V_b	Bulk velocity
V_c	Capsule velocity
W	Average Couette or pressure flow through an incremental section
$\left(\frac{\Delta P}{L}\right)_c$	Capsule pressure gradient (eqn. 2).
ΔP_f	Pressure drop between taps with liquid only
ΔP_m	Pressure drop between taps with liquid and capsules
ν	Liquid kinematic viscosity
ρ	Liquid density
σ	Ratio of capsule to liquid density

INTRODUCTION

The behaviour of a cylindrical capsule carried by means of a liquid in either laminar or turbulent flow through a pipe was predicted by Garg and Round (1) in 1970. In order to verify the turbulent flow predictions while no such experimental data existed at that time, they used an extrapolation of the laminar flow data published by Kruyer, et al. (2). The comparison, therefore, provided only a token verification as far as turbulent flow was concerned. Experimental data for capsules in water in turbulent flow subsequently obtained from a 1 1/4 inch pipeline have permitted the presentation here of a more comprehensive comparison of the above prediction with measured data.

The theory of Garg and Round is based upon the supposition that the flow of liquid in a pipe past a cylindrical capsule with its axis parallel to the pipe can be treated as the sum of pressure flow and Couette flow. Pressure flow is the flow through the annulus due to the pressure drop per unit length of the capsule. Couette flow is the flow through the annulus due to the drag force of the capsule wall on the otherwise stationary annular liquid. The eccentricity of the capsule was accounted for by dividing the annulus into small circumferential sections. Each section was treated individually as if it were a section of a concentric annulus with the distance between the capsule and pipe walls in that particular section representing the effective hydraulic length dimension. Equilibrium flow was determined according to a balance of the shear and pressure forces on the capsule.

EXPERIMENTAL PIPELINE

The experimental data were obtained from a 44 ft. (13.4 m) long, carefully honed 1 1/4 in. (32.2 mm) copper pipeline illustrated in Figure 1. Cylindrical capsules were submerged in the liquid and injected into the pipeline from a tank which also served as the source of liquid for the pump. A four-way valve (V6) controlled the direction of flow, allowing capsules to make passes back and forth through the pipeline during the tests. A heat exchanger automatically maintained a constant liquid temperature of 92°F (33°C) which was measured by a thermometer (T_1) and a thermister (T_2). A throttle valve (V_1) controlled the liquid flow rate measured by a magnetic flow meter (F). A capsule lock provided by valves V_2 and V_3 retained the capsules at the beginning of each pass by allowing flow only through V_3 until the liquid velocity reached steady state; then flow diverted through V_2 released the capsule. Four photocells (PC_1 to PC_4) mounted opposite light sources in the pipe wall were used to determine the capsule velocities, and four pressure taps in the pipe wall (P_1 to P_4), connected to differential pressure transducers, were used to measure the pressure gradients. Valves V_4 and V_5 at the end of the pipeline provided a means for decceleration of the capsule.

EXPERIMENTAL CAPSULES

The capsules were 4 ft. long hollow stainless steel tubes fitted with endcaps of polyvinyl chloride provided with "O" rings to seal out the pipeline liquid. Thin steel rods fitting exactly in the tubes between the endcaps were used to load the capsules uniformly to the various required specific gravities. The pertinent data describing the capsules used in this report are presented in Table 1.

MEASURED PARAMETERS

The five parameters determined before carrying out the experiments were:

1. The internal pipe diameter, D = 0.1056 ft. $\pm$ 0.0001 (32.18 mm).
2. Distance between photocells 3 and 4 = 3.5 ft. $\pm$ 0.005 (1.067 m).
3. Distances between pressure taps in the pipe wall, L_p = 15 ft. $\pm$ 0.05 (4.57 m).
4. Capsule length, L_c = 4.02 ft. $\pm$ 0.005 (1.225 m).
5. Average capsule diameter, d, ft. $\pm$ 0.0005.
6. Ratio of capsule to liquid density, σ, dimensionless, $\pm$ 0.005.

MEASURED VARIABLES

The five variables determined during the experiments were:

1. Liquid velocity, V_b, in ft./sec., calculated from the liquid flow.
2. Liquid temperature, controlled to 92°F $\pm$ 1 (33°C).
3. Pipe liquid pressure drop without a capsule between the pressure taps, ΔP_f, in lb./ft.^{2}
4. Pipe liquid pressure drop with a capsule between the pressure taps, ΔP_m, in lb./ft.^{2}
5. Capsule velocity, V_c, in ft./sec.

Each of the transducers for measuring the variables during the experiments was calibrated previously and on a regular basis during the experiments.

Data acquisition of the signals was accomplished with five electronic counters interfaced with a PDP-8-S computer. Voltage-to-frequency converters connected between four transducers and four counters provided frequencies directly proportional to the variables being measured, while the fifth counter, used for measuring time, was connected to its own internal oscillator. During a capsule pass through the pipeline all five counters were started simultaneously as the capsule interrupted the light beam of photocell 3. Pulses proportional to the variables being measured were then allowed to accumulate on the register of each counter until the capsule interrupted the lightbeam of photocell 4 at which time all the counters were stopped. The average value of each variable during the capsule pass was then calculated by dividing the accumulated count on each counter by the time of transit as shown by the fifth counter. The capsule velocity was obtained by dividing the distance between the two photocells by the time of transit. A capsule run represented a large number of capsule passes for the same capsule at different flow velocities.

There was no way of measuring accurately the eccentricity of the capsule in the pipe, which is one of the required parameters in the theoretical predictions of Garg and Round.

DERIVED VARIABLES

The annular liquid velocity and the capsule pressure gradient, the Reynolds number and the friction factor, which are derived variables, were calculated as follows:

From a flow balance the annular liquid velocity:

$$V_{an} = \frac{V_b - k^2 V_c}{1 - k^2}, \text{ ft./sec.} \qquad [1]$$

where the diameter ratio (k) is the ratio of the capsule diameter to the pipe diameter.

The capsule pressure gradient, defined as the pressure drop per unit of capsule length:

$$\left(\frac{\Delta P}{L}\right)_c = \frac{\Delta P_m - (L_p - L_c)\left(\frac{\Delta P_f}{L_p}\right)}{L_c}, \text{ lb./ft.}^3 \qquad [2]$$

where the distance between the pipeline pressure taps used, L_p, and the capsule length, L_c, are measured parameters. The end effects are included in the aforementioned derivation of capsule pressure gradient but these are presumably negligible for the 4 ft. long capsules.

The annular Reynolds number:

$$Re = (D - d)V_{an}/\nu \qquad [3]$$

Since water was used for the carrier liquid, its kinematic viscosity, ν, and density, ρ, were determined from the average thermister temperature of 92°F to be:

ν = 8.1×10^{-6} ft.^{2}/sec. (0.75 mm^2 s^{-1})

and ρ = 62.0 lb./ft.^{3} (993 kg m^{-3})

The annular friction factor:

$$f = (\frac{\Delta P}{L})_e \frac{2 g_c D}{\rho V_{an}^2} \quad [4]$$

Both the annular Reynolds number and the annular friction factor, which may be defined in several ways, were made consistent with the expressions initiated by Garg and Round.

COMPUTER PROGRAM SUMMARY

The computer program, which was written according to the theory developed by Garg and Round, can be found in its entirety in the M. Eng. thesis of Garg (3). It required the selection of pipe diameter, liquid viscosity and density, capsule diameter, eccentricity and capsule pressure gradient. The capsule velocity and annular liquid velocity were then calculated.

As described by Garg and Round (1) the eccentric annulus was divided into 120 radial sections. Velocity profiles for Couette and pressure flow in concentric annuli were used to calculate the forces in each radial section. Eccentricity of the capsule was accommodated by treating each radial section as if it were a section of a concentric annulus with a different diameter ratio for each section to allow for the radial variation of distance between the pipe and capsule walls in the eccentric annulus. A capsule velocity was selected and the shear and pressure forces were determined in each section and summed for the whole annulus. When these forces were not in balance a new capsule velocity was selected following the secant method (4) and the forces recalculated. This was repeated until a balance of forces was established, thus resulting in the equilibrium capsule velocity for the selected capsule and pipe geometry, liquid properties and capsule pressure gradient. The corresponding equilibrium annular velocity was then calculated by summing the flow in each radial section and dividing this sum by the annular cross-sectional area.

The theory developed for this program made the assumptions that there was no solid-solid friction between the pipe and capsule walls, that the capsule was parallel to the pipe wall and that end effects could be ignored. Local Reynolds numbers were defined as $4 AW/P\nu$ with A the area of the section, P the wetted perimeter and W the average Couette or pressure flow velocity through the section. Transition from laminar to turbulent Couette flow was assumed when the local Couette Reynolds number exceeded 2400. The velocity profiles used for turbulent Couette flow were considered valid for diameter ratios down to 0.90. Transition from laminar to turbulent pressure flow was assumed when the local pressure Reynolds number exceeded 2100. The pressure and Couette flow were each treated individually as far as transition from laminar to turbulent flow was concerned. For an individual section the Couette and pressure flows therefore could both be laminar, one laminar and the other turbulent, or both turbulent.

For the purpose of the present paper, computer calculations were performed by selecting a particular eccentricity and calculating the equilibrium capsule and annular liquid velocities for several capsule pressure gradients. Equilibrium friction factors and Reynolds numbers were then calculated from the results obtained. This was repeated for several eccentricities. Figure 2 is a plot of the results presented as a prediction of the relationship between the annular Reynolds number and the friction factor for the selected pipe diameter of 0.1056 ft., water viscosity of 8.072×10^{-6} ft.^{2}/sec. and density of 62.00 lb./ft.^{3} and capsule to pipe diameter ratio of 0.890. Figure 3 is a plot of the same results presented as a prediction of the relationship between the annular Reynolds number and the capsule velocity. The values of n in the Figures represent the capsule to pipe eccentricity according to:

$$e = (2^n - 1)/2^n \quad [5]$$

where e represents the distance between the capsule and pipe centers divided by the difference of the pipe and capsule radii. The selected values of n from 5 to 19 are for capsules of high eccen-

tricity (0.96875 to 0.9999981). The results from these were found to be in the same range as the experimental data. The symbols in Figures 2 and 3 represent the results of the actual calculations with smooth lines drawn through them to obtain the intermediate results.

COMPARISON BETWEEN PREDICTION AND MEASUREMENT

Figure 4 presents the relationship between the annular Reynolds number and the friction factor while Figure 5 presents the relationship between the Reynolds number and the capsule velocity for experimental data from the 1 1/4 inch pipeline. These data are for the same pipe size, capsule diameters and liquid properties as the theoretical prediction in Figures 2 and 3.

The theoretical prediction presents, for a number of eccentricities, the relationships between the Reynolds number and the friction factor and between the Reynolds number and the capsule velocity. While eccentricity is a major factor governing the behaviour of a capsule in a pipeline, there is, as yet, no way of measuring it experimentally to the desired accuracy. However photographic studies by Liddle (5) have strongly suggested that the eccentricity for all capsules decreases with increasing capsule or liquid velocity and, in general, decreases from front to rear over the capsule length at a given velocity. This implies that when the experimental friction factors or the experimental capsule velocities are plotted as a function of annular Reynols number, the value of eccentricity varies continuously over the whole curve though it cannot be specified. However, the computer program requires a certain eccentricity to be specified beforehand, and this value is kept constant for the entire theoretical curve. Thus if the computer program is run for different eccentricities over the same capsule velocity range and the results superimposed on the experimental data, the theoretical curves will intersect the experimental curves at discrete points on both the plots of Reynolds number versus friction factor and the plots of Reynolds number versus capsule velocity. Figures 6 and 7 show this for the capsules with a diameter ratio of 0.890 having a range of experimental density ratios from 1.031 to 5.000 and the range of theoretical eccentricities given before. Capsule to liquid density ratios can be determined from the run numbers in the Figures according to Table 1. Only the first and last curve show the run numbers in Figure 7 to reduce congestion of the plot.

Since the theoretical curves represent friction factors, Reynolds numbers, and capsule velocities which are in equilibrium, the theory is verified by experiment when there is agreement between the theoretical and the experimental curves in the relationship of the friction factor,, the Reynolds number and the capsule velocity. Therefore, the Reynolds number for a constant friction factor and the Reynolds number for a constant capsule velocity must be identical for theory and experiment. Tests for agreement were made at the intersection points of the experimental and the theoretical curves. The intersection Reynolds numbers in Figure 6 were compared with the intersection Reynolds numbers in Figure 7 and the results are presented in Table 2. The points of intersection that matched Reynolds numbers to within 10% were considered to indicate verification and these are shown by circles while those for which the difference was greater are marked by crosses in Figure 6.

Inspection of the Figures shows that intersection points are more difficult to determine for Figure 7 than for Figure 6 since the intersection angles of the former are much more acute than those of the latter. For this reason Figure 6 was used to show the verified points. The verified intersections are shown in both plots; however, Figure 7 shows a larger number of unverified intersections.

The same comparisons were made for two other diameter ratio capsules. These are presented in Figures 8 and 9 and Table 3 for a diameter ratio of 0.940 and in Figures 10 and 11 and Table 4 for a diameter ratio of 0.839.

It is important to note from equations 1 and 3 that the Reynolds number is defined according to a partial subtraction of the capsule velocity from the average liquid velocity. An agreement between theoretical and experimental Reynolds numbers of 10% therefore will represent an agreement between theoretical and experimental average liquid velocities of better than 3% for the capsules here presented.

RESULTS

As shown by the circles in Figures 6, 8 and 10, the agreement between the theory and experiment is good except at the bottom right of the plots representing high velocities for the low density capsules and at the top left of the plots representing low velocities for the high density capsules. Such discrepancies however are expected since in the former case the eccentricity is not uniform over the capsule length, while the theory assumes it to be uniform. In the latter case, the solid-solid friction at low velocities is too important to be neglected. The annular liquid velocity before movement of high density capsules is quite high, though the theory, being for a frictionless capsule-pipeline system, takes it to be zero. In general, the number of discrepancies is more for $k = 0.839$ but this is probably due to unsatisfactory velocity profiles for turbulent Couette flow when the diameter ratio is less than 0.9. On the whole, however, there are enough points of agreement to indicate, for large diameter ratios, the validity of the theory of Garg and Round for long frictionless capsules moving parallel to the pipe wall.

CONCLUSIONS

Agreement between the predicted and the measured Reynolds numbers for constant friction factor and capsule velocity was within 10% for most of the data tested, showing the validity of the theory by Garg and Round (1). Heavy capsules at low velocities and light capsules at high velocities showed no agreement but these cases probably violated the basic assumptions of the theory.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the Transportation Development Agency for financial support for this work.

The work by Mr. E. J. Parranto as operator of the experimental pipelines is gratefully acknowledged.

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TABLE 1

CAPSULE DESCRIPTIONS

Run number	L_c	k	σ
409	4.02 ft. (1.225 m)	0.940	1.031
417	"	"	1.125
425	"	"	1.250
433	"	"	1.500
441	"	"	2.000
457	"	"	5.000
411	"	0.890	1.031
403	"	"	1.063
419	"	"	1.125
427	"	"	1.250
543	"	"	1.500
443	"	"	2.000
451	"	"	3.000
459	"	"	5.000
413	"	0.839	1.031
405	"	"	1.063
421	"	"	1.125
429	"	"	1.250
437	"	"	1.500
445	"	"	2.000
453	"	"	3.000

TABLE 2

COMPARISON BETWEEN EXPERIMENT AND THEORY FOR k = 0.890

	Fig. 6		Fig. 7				
n	Re	f	Re	V_c	σ	Symbol	Run
9	660	0.330	710	0.40	1.031	o	411
7	1400	0.118	1450	1.20	1.031	o	411
5	3200	0.041	2000	2.10	1.031	x	411
11	930	0.320	1500	0.67	1.062	x	403
9	1500	0.165	1700	1.20	1.062	o	403
7	2200	0.081	2200	2.00	1.062	o	403
5	5000	0.031	3200	3.50	1.062	x	403
11	1650	0.220	1900	0.90	1.125	x	419
9	2400	0.115	2400	1.75	1.125	o	419
7	3900	0.052	3000	2.75	1.125	x	419
13	2200	0.230	2500	0.90	1.250	x	427
11	2600	0.160	2600	1.35	1.250	o	427
9	3600	0.089	3500	2.75	1.250	o	427
17	3300	0.220	3500	0.90	1.500	o	543
15	3300	0.210	3600	1.15	1.500	o	543
13	4000	0.160	4000	1.70	1.500	o	543
11	4600	0.110	4600	2.75	1.500	o	543
17	5100	0.165	5600	1.90	2.000	o	443
15	5300	0.155	6000	2.30	2.000	x	443
13	6000	0.125	6000	2.90	2.000	o	443
17	10,000	0.112	10,000	4.20	3.000	o	451
15	10,000	0.102	10,000	4.50	3.000	o	451

TABLE 3

COMPARISON BETWEEN EXPERIMENT AND THEORY FOR k = 0.940

n	Fig. 8 Re	Fig. 8 f	Fig. 9 Re	Fig. 9 V_c	σ	Symbol	Run
7	350	0.55	350	0.75	1.031	o	409
5	730	0.155	1000	2.20	1.031	x	409
11	450	0.91	450	0.45	1.125	o	417
9	620	0.48	650	0.93	1.125	o	417
7	1120	0.275	1100	2.05	1.125	o	417
5	2000	0.62	1600	3.35	1.125	x	417
13	700	0.80	750	0.60	1.250	o	425
11	950	0.43	950	0.92	1.250	o	425
9	1300	0.225	1300	1.88	1.250	o	425
7	2300	0.088	1600	2.90	1.250	x	425
13	1200	0.49	1570	1.30	1.500	x	433
11	1550	0.31	1680	1.95	1.500	o	433
9	2200	0.155	1950	3.00	1.500	x	433
17	2000	0.43	2200	1.40	2.000	o	441
15	2100	0.40	2300	1.65	2.000	o	441
13	2200	0.32	2400	2.20	2.000	o	441
11	2750	0.195	2750	3.65	2.000	o	441

TABLE 4

COMPARISON BETWEEN EXPERIMENT AND THEORY FOR k = 0.839

n	Fig. 10 Re	Fig. 10 f	Fig. 11 Re	Fig. 11 V_c	σ	Symbol	Run
7	2900	0.60	2900	1.70	1.031	o	413
5	7000	0.24	4000	2.80	1.031	x	413
9	1700	0.13	2900	1.35	1.063	x	405
7	3700	0.051	3800	2.10	1.063	o	405
11	3300	0.11	3900	1.30	1.125	x	421
9	4600	0.064	4600	2.15	1.125	o	421
7	7200	0.032	5800	3.5	1.125	x	421
15	4300	0.133	4800	0.90	1.250	x	429
13	4600	0.115	5100	1.25	1.250	o	429
11	5400	0.081	5900	2.20	1.250	o	429
9	8600	0.042	7100	3.80	1.250	x	429
19	5200	0.120	5700	1.00	1.500	o	437
15	5300	0.115	6000	1.20	1.500	x	437
13	5500	0.100	6600	1.80	1.500	x	437
11	7000	0.068	7200	2.80	1.500	o	437
19	9600	0.091	11,000	2.40	2.000	x	445
15	10,000	0.086	11,000	2.80	2.000	o	445
13	11,000	0.068	12,500	4.20	2.000	x	445

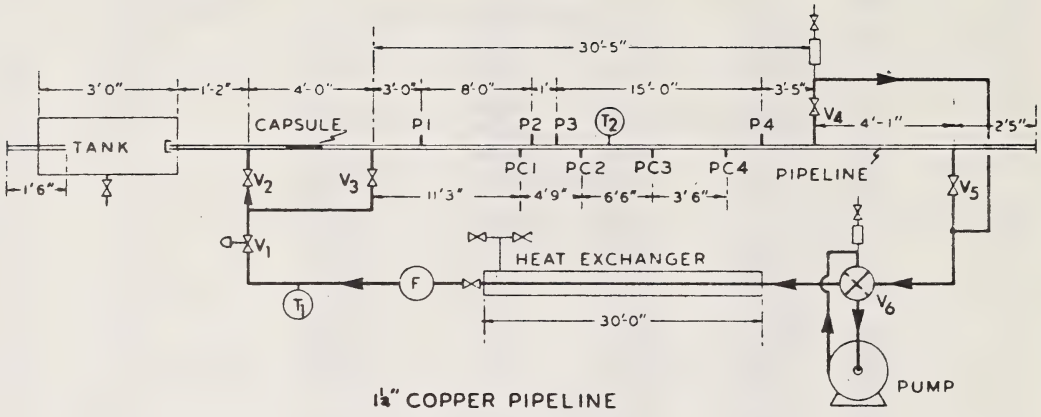


FIG. 1. Schematic of the Experimental Pipeline

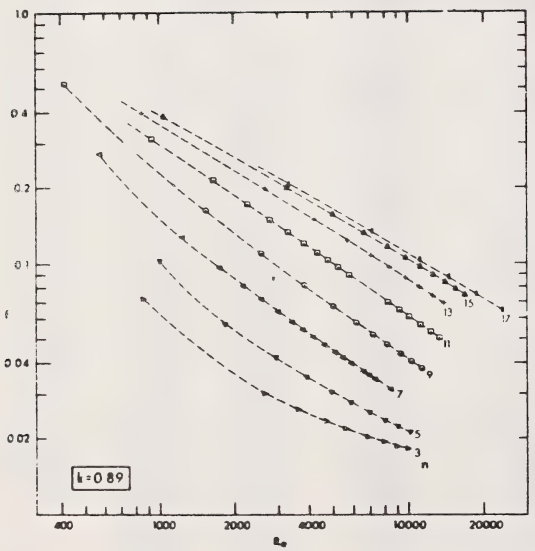


FIG. 2. Theoretical Predictions of the relationship between Annular Reynolds number and friction factor for k = 0.890 at various eccentricities

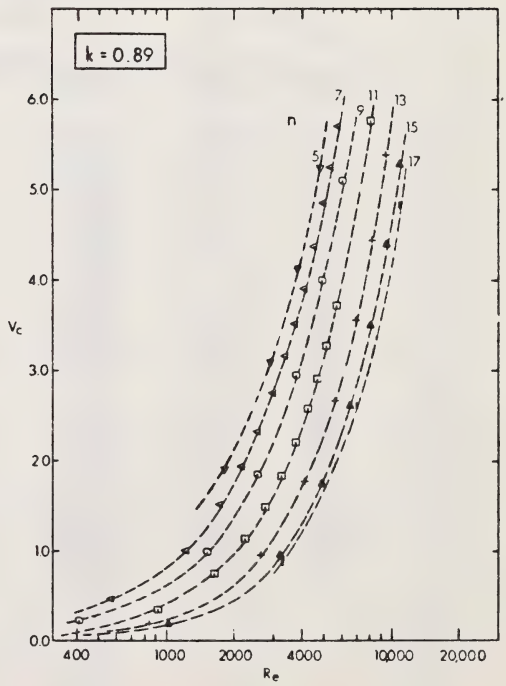


FIG. 3. Theoretical predictions of the relationship between the Reynolds number and the capsule velocity for k = 0.890 at various eccentricities

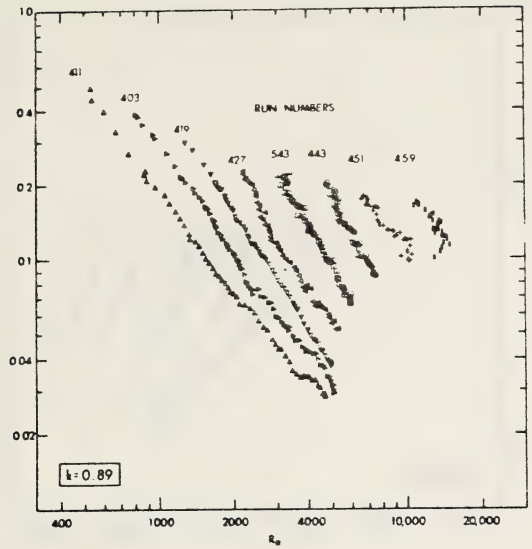


FIG. 4. Experimental relationship between Reynolds number and friction factor in the 11/4 inch pipeline for k = 0.890

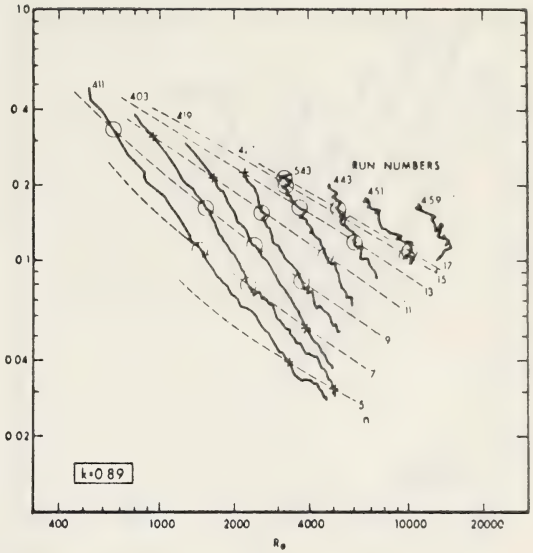


FIG. 6 Comparison between Experiment and theory for k = 0.890. Solid lines are experimental results and dashed lines are theoretical predictions

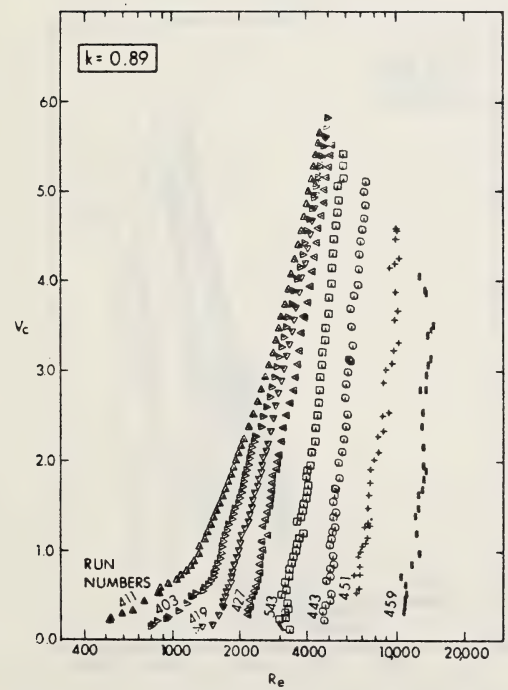


FIG. 5. Experimental relationship between Reynolds number and Capsule velocity in the 11/4 inch Capsule pipeline for k = 0.890

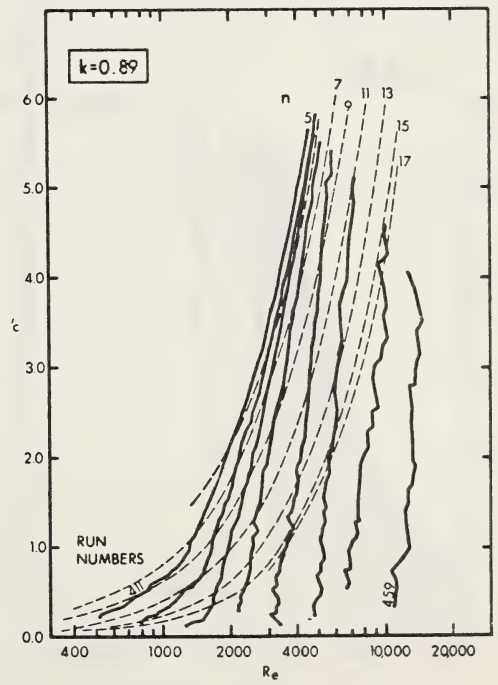


FIG. 7 Comparisons between experiment and theory for k = 0.890. Solid lines are experimental results and dashed lines are theoretical predictions.

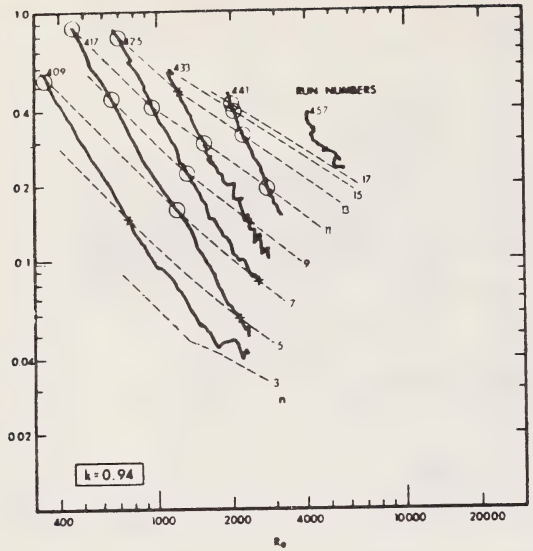


FIG. 8 Comparison between experiment and theory for k = 0.940

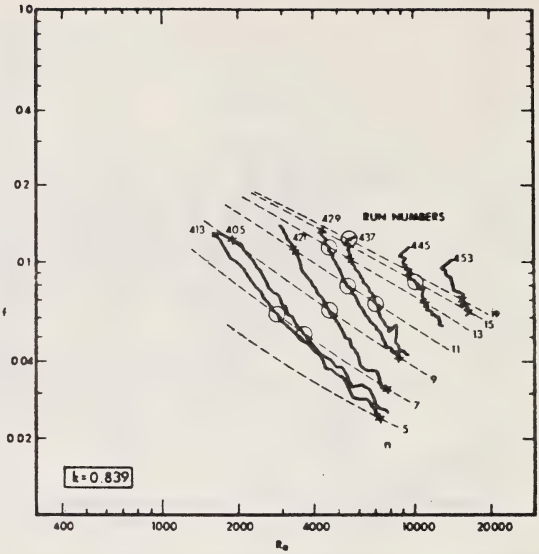


FIG. 10 Comparison between experiment and theory for k = 0.839

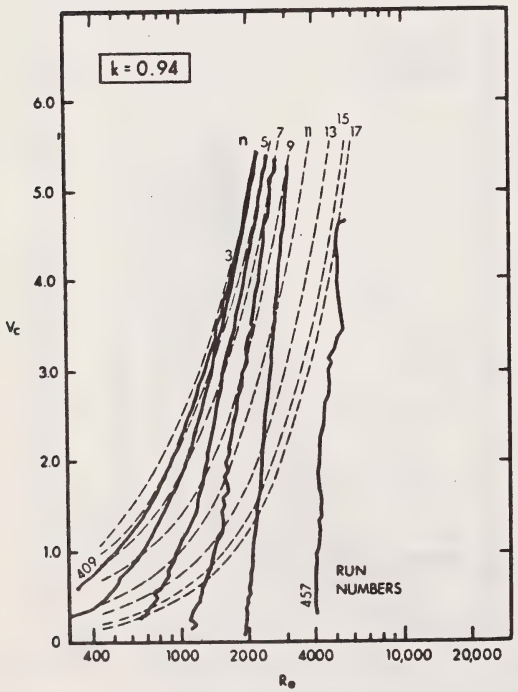


FIG. 9 Comparison between experiment and theory for k = 0.940

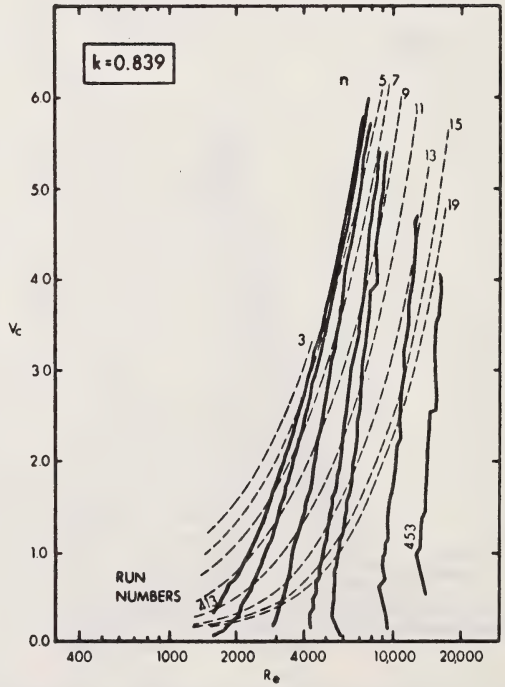


FIG. 11 Comparison between experiment and theory for k = 0.839

CHAPTER IV

University Support Programs

CHAPTER IV

University Support Programs

The TDA-RCA contract stipulates that grants can be made available to post-graduate students. "Such costs would not be expected to exceed about 10% of the overall project costs".

In accordance with this provision, research proposals and applications for grants were received in May 1971 from:

Dr. K. Aziz, Dept. of Chemical Engineering, University of Calgary
Dr. J. K. Donnelly, Dept. of Chemical Engineering, University of Calgary
Dr. N. Epstein, Dept. of Chemical Engineering, University of British Columbia
Dr. D. Quon, Dept. of Chemical & Petroleum Engineering, University of Alberta
Dr. G.F. Round, Dept. of Mechanical Engineering, McMaster University.

The letter of invitation (attached) that preceded these applications was accompanied by an outline of problems relevant to the TDA-RCA project, but it was emphasized that areas other than those listed would be considered.

Two proposals (attached) were accepted. They were:

A. D. Quon and H. Singh - Statistical Model Building as Related to Capsule Pipelining.
B. N. Epstein and R.J. Bianchi - Eccentric Laminar Couette Flow in a Cylindrical Capsule Pipeline System.

Terms of the grants were subsequently negotiated and agreed upon.

The total cost of A is $20,700
B is $15,440.

A. University of Alberta Program

A comprehensive report entitled "The Pipeline Flow of Capsules, Report No. 1, Empirical Capacity and Pressure Correlations for Cylindrical Capsules Conveyed in $\frac{1}{2}$" and $1\frac{1}{4}$" Pipelines", by H. Singh and D. Quon, was received in December, 1971. It was attached to Bi-monthly Progress Report No. 7.

B. University of British Columbia Program

A preliminary progress report (attached) was received in March, 1972 from Mr. R.J. Bianchi. This was followed by a 4th year thesis entitled: Eccentric Laminar Couette Flow in Cylindrical Capsule Pipeline System. The abstract of this thesis is appended and the full text of this thesis is available either from the University of British Columbia library or from the Research Council of Alberta.

PROVINCE OF ALBERTA

RESEARCH COUNCIL OF ALBERTA

11315 - 87TH AVENUE
EDMONTON 7, ALBERTA, CANADA

OUR REF:

May 10th, 1971

Capsule Pipeline Research

Dear Dr. XXX:

The attached statement outlines a number of problems relating to our current pipeline research project which may be of interest to the Universities. Our contract with the Transportation Development Agency runs for three years, and a certain amount of funds will be available to support university research throughout this period. The TDA has expressed a strong preference for using these funds to support graduate thesis programs, preferably at the Doctoral level but alternately at the Master's level, so that graduates with an interest in solids pipelines might be produced as an additional benefit.

I should emphasize that these suggested problems represent only our current views, and it is very likely that additional problems will become evident as the work progresses. Also, there is considerable room for negotiation in formulating problems that will meet academic needs while still being useful to us.

I would therefore like to invite proposals on any or all of the problems outlined in the attached statement. I also hope that interested faculty members will feel free to arrange meetings with our own staff at any mutually-convenient time to discuss the objectives and current status of the capsule pipeline research project in as much detail as they wish. Further suggestions for research will always be welcomed.

Yours sincerely,

E. J. Wiggins
Director

EJW/BWB

PROVINCE OF
ALBERTA

RESEARCH COUNCIL OF ALBERTA

11315 - 87TH AVENUE
EDMONTON 7, ALBERTA, CANADA

OUR REF:

PROJECT ON CAPSULE PIPELINING HYDRODYNAMICS

sponsored by

CANADIAN TRANSPORTATION DEVELOPMENT AGENCY

Proposed Problems for Theoretical and Mathematical Analysis to be Undertaken in University Research Programs.

A general line of approach to the understanding of the hydrodynamics of capsule pipeline transport has been developed in previous publications from the Research Council of Alberta and this will be continued both theoretically and experimentally during the current TDA-sponsored research project. Although considerable progress has been made in the development of generalized equations that will correlate all of the pertinent measurable variables in any practical capsule pipeline, we are still far from a complete theoretical understanding or from fully predicting behavior over a wide range of variables. Empirical and semi-empirical approaches have been fairly successful over limited ranges of the variables.

We believe that this field of study is one that may well be of interest to members of University Engineering faculties and that it will be possible to decide on projects which are both academically interesting and pertinent and useful to the Research Council. The following list of problems is presented in terms of their importance from our point of view. We hope this will be the initiation of a dialogue between interested University engineers and members of the Research Council pipeline group that could lead to agreement on a mutually satisfying research program. The list has been divided up into problems of increasing difficulty which should be undertaken in this sequence (except for sections 5 and 6), but not necessarily by the same person. Periodic consultation with the Research Council is regarded as a requisite for these investigations, primarily because related work will be carried out at the Research Council.

....

The results of the work on each section should be presented in the form of a report, giving a precise description of the technique, including all the pertinent equations if the solution is analytical, or all the required steps if the solution uses a numerical approach. This description should be accompanied by a tested computer program which can be run on the Research Council (PDP-9) or University of Alberta (System 360) computers. Some sample results of the computer solution should be included in the report.

Cylinders

1. For a solid cylinder drawn through a straight, horizontal, hydraulically smooth pipe filled with a stationary incompressible liquid, determine the distribution of pressure and shear at the cylinder wall and the moments on the cylinder. The particular approach is left open to the investigator. Results should be obtained for the following range of variables:

cylinder/pipe diameter ratio (k):	0.85 to 0.95
cylinder velocity (V_c):	0 to 10 f.p.s.
buoyed capsule S.G. ($\sigma - \rho$):	0 to 8
mean clearance under capsule/pipe diameter (C/D):	0 to 0.01
angle of capsule to pipe axis (θ):	0 to 2°
liquid viscosity (ν):	0.5 to 500 cs.
pipe diameter (D):	1 to 48 in.
cylinder length (L):	2 to 10 D

End effects and solid-solid friction should be ignored.

2. Relate the variables of 1 to give a stable capsule (all forces balance and the net moment is zero).

3. (a) Repeat 1 and 2 for a free-flowing frictionless cylinder with laminar flow in the pipe and mean liquid velocities, V_{av}, to give a range of velocity ratios, V_c/V_{av}, from 0 to 1.2. Calculate the pressure gradient along the cylinder for each stable condition and state the mean capsule clearance and angle.

(b) Repeat 3(a) with turbulent flow in the free pipe.

4. (a) Repeat 3 for a range of coefficients of friction from 0.00 to 0.30 for each value of V_c/V_{av}, using the reaction between cylinder and pipe (which decreases as capsule velocity increases), for the calculation of solid friction lubricated by the pipeline fluid.

(b) Repeat 4(a) for a range of pipe inclines from 0° to 30°.

.....

Spheres

5. Determine for the following range of variables the pressure gradient and shear distribution for a train of spheres rolling horizontally in a pipe full of flowing fluid, both for laminar and turbulent flow:

sphere/pipe diameter ratio:	0.85 to 0.95
sphere velocity:	0 to 10 f.p.s.
buoyed sphere S.G.:	0 to 8
liquid viscosity:	0.5 to 50 cs.
pipe diameter:	1 to 48 in.
distance between sphere centres:	1.0 to 5.0 sphere diameters
solid-solid static friction coefficient:	0.1 to 0.4
rolling friction coefficient:	0 only

6. Repeat 5 for a range of pipe inclines from 0 to 30°.

Statistical Model Building

One of the primary aims of any engineering research program is to produce a mathematical description of the physical phenomena in sufficient detail and with sufficient accuracy such that it can be used for design purposes. Hopefully, the physics of the phenomenon are sufficiently understood so that the form of the mathe matical model can be established; except in some very simple cases, the parameters must then be estimated from experimental data. In other cases, even the form of the model is in doubt; and we have to resort to empirical or correlative models. In almost all cases, even after extensive experimentation and after testing a variety of models, there still remains uncertainty--both about the validity of the model form and about the parameters. It is the task of statistics to quantify this uncertainty, to make probability statements about these models. Putting it another way, we try to make a meaningful assessment of the reliability of a predictive design equation. Recently, there has been an extension of this kind of analysis into an area which is called statistical decision theory. Central to this analysis is an evaluation of the cost of uncertainty; for example, what is the economic cost of building a pipeline based on a design equation that predicts 25% low or 25% high? Knowing the probabilities of such high or low predictions, we can compute the expected cost of uncertainty. If this cost is too high, we can try to reduce it by looking for better models or by further experimentation. But these efforts themselves cost money. Statistical decision theory tells us when a design equation is good enough for its intended purpose.

Application to Capsule Pipelining

We plan then to apply statistical methods to the existing data on capsule pipeline flow with the hope of developing a suitable design equation, and also with the object of pinpointing the areas of uncertainty to aid in logically planning further experiments.

The model forms to be tested will be of two types: those arising from basic theoretical analysis, based on hydrodynamic considerations; and those which are essentially empirical or correlative in nature. While it is expected that the expertise for suggesting model forms will come from those research workers at the R. C. of A. with long experience in this area, provision has been made for possible consulting services of Prof. F. A. Seyer of the Department of Chemical and Petroleum Engineering to provide theoretical back-up.

To illustrate the approach, we might use as a starting point the recent correlation suggested by Ellis and Kruyer (Part 10) in which is introduced the concept of an equivalent velocity V_{eq} defined as:

$$V_{eq} = V_{an} - A\,V_c \qquad (1)$$

where V_c is an observed quantity (capsule velocity), V_{an}, the annular velocity, which is easily calculable from observable quantities, and A is an empirical question. The equivalent diameter is defined as:

$$D_{eq} = D - d \qquad (2)$$

The idea is that the use of an equivalent velocity and an equivalent diameter will permit all the capsule flow data to fall on the standard Fanning friction factor versus Reynolds number curve. The authors, using informal, intuitive methods, show that there exists an optimal value of A, which would tend to bring the data together on one curve, although in the

laminar range A is a function of pipe diameter, suggesting that a more complicated correlation may be required.

We think it is fair to say that a definitive model does not yet exist even in determining the relation between liquid velocity and pressure gradient for a given capsule velocity. What is certainly not established is a predictive relation between liquid velocity and capsule velocity.

The advantages of a formal, computerized systematic statistical analysis of the data are:

1. For a given model form, it permits an objective "best fit" estimate of the unknown parameter, with the desirable properties of unbiasness, efficiency, and consistency.

2. It permits a quantitative evaluation of the quality of the fit between the model predictions and the data. As a consequence, we can estimate the reliability of the model.

3. Because of the speed and efficiency of the computer in carrying out the above tasks, it frees the experimental investigator to do what he is most capable of doing, namely, suggest model forms suitable for testing.

4. Because of the computational capabilities of the computer, complex model forms involving many parameters can be analyzed. A study of the literature on complex multi-phase flow phenomenon in such areas as fluidization and two-phase flow suggests that we may indeed require multi-parameter models to adequately describe capsule pipeline flow.

The request for proposal issued by the Research Council of Alberta suggested a theoretical and experimental program to investigate and determine if possible the basic hydrodynamics of capsule pipelining. While the objective is laudable, it is only fair to point out that even in much simpler flow cases, the basic fluid mechanics is not completely understood.

Certainly, in areas like fluidization and two-phase flow, and even in liquid pipelining (turbulent flow), we still resort to empirical, correlative models. If we want to get a workable design equation, then it seems to us that at this point, there is no alternative to using the techniques of statistical model building.

The doctoral student involved in this proposal is Mr. Harbajan Singh, who has just completed his M.Sc. degree under my direction. The title of his thesis is "Bayesian Statistical Methods in Model Discrimination and Model Building". The methodology and the computer programs developed in this work are directly applicable to the model-building program suggested by the Research Council. A copy of a paper describing these techniques is attached. Mr. Singh's thesis is also available.

A two-year budget is attached.

May 31, 1971

Respectfully submitted,

Donald Quon

Donald Quon, Professor of
Chemical Engineering

THE UNIVERSITY OF BRITISH COLUMBIA

VANCOUVER 8, CANADA

DEPARTMENT OF CHEMICAL ENGINEERING

June 3, 1971.

Dr. E. J. Wiggins,
Research Council of Alberta,
11315 - 87th Avenue,
Edmonton 7, ALBERTA.

Dear Dr. Wiggins:

Many thanks for your considerate letter of May 27th inviting me to become involved again in hydrodynamic problems relevant to capsule pipelining. I would indeed be interested in undertaking the following problems, the first of which I was in any case planning to look into.

A. Laminar Fully Eccentric Flow in an Annulus: Discrepancy Between Theory and Experiment.

There is a disturbingly large discrepancy between the experimental data of Bourne, Figueiredo, and Charles (Can. J. Chem. Eng. 46, 289, 1968; 47, 444, 1969), whose measured values of friction factor - Reynolds No. product show a minimum at diameter ratio = 0.75, and the theoretical fully developed values computed from the infinite series solution of Caldwell (J. Royal Tech. College, Glasgow, 2, 203, 1930), which show no such minimum at all. One possibility to be checked out is that the infinite series has not been correctly evaluated. Another more likely source of the discrepancy is that the 3 - ft entrance length used by Bourne et al. may have not been sufficient to remove entrance effects from their measured pressure drops. An experimental apparatus in our laboratory which has previously been used to make very extensive measurements on the developing pressure gradient for laminar, transition and turbulent flow through ducts with rod clusters, open circular tubes and concentric annuli is ideally suited for measuring and eliminating entrance effects in eccentric annuli. A schematic of the apparatus is show in Figure 1 of the enclosed pink-covered reprint. Although the equipment

has been somewhat modified and cannibalized since our last studies, it should be possible to restore it to working order with a modest expenditure of money, time and effort.

B. Problems 1, 2 and 3(a) of your TDA - sponsored Project on Capsule Pipelining Hydrodynamics.

Theoretical solutions are available in the literature for laminar flow, including zero flow, of a Newtonian fluid in a circular pipe with a cylindrical moving or non-moving eccentrically located core. These solutions can be applied to solving the 0° cases. For zero angle and zero clearance, the resolution of problem A above will be helpful. For angles greater than 0°, detailed numerical analysis will have to be resorted to. The enclosed blue-covered reprint and the xeroxed reprint indicate the type of experience we have had with numerical analysis. We would only consider looking at problems 3(b) and 4 after we had adequately solved problems 1 - 3(a).

As for the actual personnel to be involved in doing this work, since I presently have five graduate students working with me and a sixth due in September, I would not want to undertake supervision for any additional graduate students this fall, particularly in view of an economic situation which is even more adverse for post-graduate degree students than for graduates. There is a very slight possibility that the doctorate student due to arrive in September could opt for capsule work, but it is far more likely that he will prefer a sedimentation problem which we have previously discussed.

I would therefore propose that the solution of the above problems be initiated by one or two final year undergraduate students for their Bachelor's thesis projects, under my supervision. These students would be selected for their mathematical and computational aptitude, and for their interest in the given problems and in possibly going on to do graduate work in capsule pipelining. That way we would delve gradually into the problems, getting a feel for the work involved, and little or no financial support would be required from you for the first year except for any expenses incurred due to periodic consultations with the Research Council.

An added possibility is to also put a postdoctoral research fellow to work on the probable experimental side of problem A. This would entail some minor equipment support from you as well as payment to the research fellow of a standard N. R. C. graduate student salary (currently $265 per month), the balance of the man's salary to be paid by me out of my N. R. C. operating grant.

I would welcome your reaction to the above proposals. I will want to firm up my research plans for the coming academic year by the end of the summer.

Sincerely yours,

Norman Epstein

Norman Epstein,
Professor.

NE/nb

Enclosures.

CAPSULE PIPELINING HYDRODYNAMICS

Preliminary Progress Report March 23, 1972

Distributions of shear stress and twisting moment have been evaluated for a longitudinally aligned cylinder drawn through a straight horizontal pipe filled with a stationary, incompressible Newtonian fluid (Couette flow). Shear stresses along the pipe wall have also been calculated for the same set of conditions. The results were obtained using a computer program for diameter ratios ranging from 0.85 to 0.95 in increments of 0.01 and clearance ratios ranging from 10^{-6} to 10^{-2} in cycles of 10. The upper clearance range of 10^{-3} to 10^{-2} was treated in more detail using increments of 0.002.

Shear stresses were evaluated from derived analytical equations, while numerical techniques were used to integrate an expression for the twisting moment. The expressions for both shear stresses and twisting moment contained core velocity, fluid viscosity and pipe diameter as linear terms. This property reduced the number of systems to be analyzed to various combinations of two independent variables, specifically cylinder to pipe diameter ratio and clearance to pipe diameter ratio. The fixed parameters were taken for convenience to be:

Fluid viscosity	=	10 centipoises
Capsule velocity	=	1 ft/sec
Pipe diameter	=	1 foot

The theoretical solutions posed are valid only in the laminar flow regime. Thus to check the validity of solutions obtained for each system being considered, a calculation of Reynolds Number was required, employing a derived solution for the integrated average annular fluid velocity.

Robert J. Bianchi
Norman Epstein (supervisor)
Dept. of Chemical Engineering, U. B. C.

CHAPTER V

Experimental Program - Phase II

CHAPTER V

Experimental Program - Phase II

A. Four Inch Pipeline Facility

Experimental measurements for a large number of capsule trains have been made in the 4 inch pipeline with the butyrate test section. During the correlation of these measurements, however, it was discovered that the capsule pressure gradients for a given capsule train increased with time while the capsule velocity for the same train at a given liquid velocity decreased. This indicated that something has changed with time in the pipeline. We do not know exactly what it is but it appears that pipe roughness and friction between the capsule and the pipe wall may be the reason. Stainless steel rubbing against butyrate plastic does cause scratching of the plastic resulting in a change of the very smooth plastic surface to a rougher one. In liquid flow through pipelines the pipe roughness is presented as a hydraulic roughness and this is expressed in pipe diameters (e = roughness grain size divided by D = pipe diameter). In capsule flow this roughness in all probability should not be expressed in pipe diameters but in clearances.

Under the capsule, where the roughness is modified due to scratching of the capsule surface against the pipe the clearance in a 4 inch pipe is in the order of 10^{-3} inch or less. When the surface roughness of, for example, commercial 4 inch steel pipe ($e = 15 \times 10^{-5}$) is expressed as a hydraulic roughness for use in the usual friction factor-Reynolds number diagram to predict pipeline pressure losses, it manifests itself almost as a smooth pipe. When this roughness is related to the clearance between the capsule and the pipe, however, the effect is an extremely high relative roughness. This may be the reason why pipe roughness plays such an important part in capsule pipeline results. The complication added to this problem is that this roughness is altered as the capsules travel through the pipeline. A steel pipe tends to become smoother as the capsules travel through it while, as discovered with the butyrate pipe, plastic pipes appear to become rougher. The practical implications of this problem are evident when data from a newly constructed experimental steel pipeline (SPRDA loop) are compared with data from a worn-in pipeline of the same size (RCA 4 inch steel shuttle line). The newly constructed pipeline gave capsule

pressure drops twice as large as those obtained in the RCA pipeline where capsules had smoothed the pipe surface. The degree of smoothing that will take place in a commercial pipeline however is not known and it therefore becomes mandatory to relate the pipe roughness to the capsule pressure gradient experimentally.

Since the plastic test section can be rotated a new pipe surface can be exposed to the capsule wear in order to study this problem. One method of determining the pipe/capsule roughness may be by measuring the coefficient of friction between the capsule and the pipe surface. This test can be interspersed with the experimental work on capsule flow and the change in capsule/pipe roughness as the capsules wear the pipe can therefore be monitored. A preliminary apparatus has been constructed to pull capsules through the 4 inch pipeline and to measure the pulling force. An attempt will be made to correlate these pulling forces for capsules of various densities with the capsule pressure gradients for the same capsules. The tests will be performed several times to determine the effect of pipe wear. When this work has been completed a stainless steel test section will be installed in the 4 inch pipeline and the experimental program will continue in this test section, measuring the pressure gradients, velocities and pulling forces. During these tests the effects of train and capsule lengths will be studied along with the effects of capsule density and diameter ratio. Initial work will commence with water as the carrier liquid. When this has been completed a viscous, Newtonian liquid will be added to the water to obtain liquid viscosities between 1 and 50 centistokes.

When this work has been completed it will be repeated in a 1/2 inch pipeline. Some experimental results were obtained some years ago in a 1/2 inch experimental capsule pipeline with a heavy lubricating oil as the carrier liquid. The data from this pipeline correlate very well with theory and with results from larger pipelines up to 4 inches in diameter. It is, for this reason, felt that preference should be given to this pipe size in order to obtain data on a wide range of pipe diameters. The range of experimental measurements from 1/2 to 10 inches represents a scale up of about 16 for these schedule 40 pipes. Work with the 1/2

inch pipeline will start with a stainless steel test section with water as the carrier liquid and then with solutions of various viscosities as planned for the 4 inch pipeline. When work in the 1/2 inch line is completed a 2 inch pipeline will be brought on stream and experimental measurements will be repeated. A 1 inch pipeline will eventually be constructed if it appears that experimental work on this size is warranted.

B. Ten Inch Pipeline Facility

The operating program for the 10 inch shuttle pipeline was designed to provide further data for the mathematical models developed from the $\frac{1}{2}$ to 4 inch capsule pipeline experiments.

The data required were:

1. Liquid pressure gradients.
2. Capsule pressure gradients for a dynamic system.
3. Pressure gradients for a system where capsules remain stationary.
4. Coefficient of friction between pipe and capsules.
5. Effect of varying capsule and pipe roughness.
6. Effect of varying liquid viscosity.
7. Effect of train length.
8. Threshold velocities for various capsule trains.

To provide the above data a number of 4 foot long cylinders were prepared. They were 8.5 inches, 9.0 inches and 9.5 inches in diameter and each fitted with removable end caps to permit changing their specific gravities from 0.97 to 1.50 or higher.

Provision has also been made to modify the cylinders by changing their surface or placing bands around their circumference.

A number of aluminum and iron spheres have been prepared with the same diameters as the cylinders to provide data for geometric shapes other than cylinders.

Since the program was planned to provide additional data to other facilities, it also must remain flexible to accommodate requirements as new trends emerge.

CHAPTER VI

Four Inch Pipeline Facility

Four Inch Pipeline Facility

Figure 1 is a schematic representation of the laboratory shuttle pipeline which is straight and level and allows the shuttling back and forth of long, large diameter ratio capsules. Measurements are performed as the capsules travel through the test section in the forward direction. An injection tank allows the insertion of capsules into the pipeline without entrapping air. A cap provided with a spring and a straightening vane (Figure 2) is used to close the pipeline. The spring absorbs energy as the capsules stop on the return pass while the flow straightening vane positioned in the pipe past the liquid inlet from valve 2, reduces swirl of the entering liquid. Capsules inserted into the pipeline enter a lock between the liquid inlets from valves 2 and 3 so that, when valve 2 is closed and valve 3 is open, the capsules remain stationary while the liquid reaches steady state velocity. The capsules, now injected into the flowing liquid by closing valve 3 and opening valve 2, very quickly gather momentum and only a short distance of travel is needed to attain steady state capsule velocity. A four-way valve (V_1) determines the direction of liquid flow, while throttle valves of two sizes (V_6, V_7) are used to control the flow rate.

The pipeline consists of four sections of pipe approximately 20 feet long, joined by flanges. A brass ring, inserted in each flange concentric with the bore of the pipe, eliminates step changes in the internal diameter of the pipe at the joints (Figure 3). Smooth transparent cellulose acetate butyrate (C.A.B.) pipe of a schedule size is used because of its high impact strength and also because it is the only transparent standard size pipe readily available. Schedule 40 has been chosen to facilitate the manufacture of test sections of other materials in this standard size without changing the internal pipe diameter appreciably. The C.A.B. pipeline is mounted on a continuous mahogany cradle, supported lineally every two feet by an angle iron frame, (Figure 4). Fibreglass fittings and pipe have been used for the return lines. Three centrifugal pumps, each producing a flow of 100 USGPM at 55 psi are connected in

parallel to provide a maximum flow of about 300 USGPM representing a liquid velocity of 8 ft./sec. in the pipeline. Lower velocities are obtained by throttling the flow and by turning off one or two of the pumps when the throttling causes pressures in the pipeline in excess of 55 psi. Pressure sensitive safety switches connected at several points in the pipeline turn off all pumps when pressure exceeds 60 psi. Two safety photocells (S in Figure I) also turn off all pumps before capsules approach the pipe ends so closely that pressure shocks may cause pipe rupture. Temperature control is maintained with a 7 1/2 ton cooling unit (I ton of cooling = 200 B.t.u./min.) connected to a heat exchanger in the injection tank. A portion of the liquid stream from the pumps flows through this tank and back to the pumps to allow control of the liquid temperature to within 2 degrees Fahrenheit.

The removable pipeline test section is 20 feet long and has an internal diameter varying from 4.02 to 4.03 inches. Stainless steel tubes provided with endcaps of polyvinyl chloride and sealed with O-rings, are used as cylindrical capsules. Their densities are varied by loading them uniformly with steel rods which fit tightly between the endcaps. Capsule lengths are kept constant to within 0.05 inches and maximum variation in diameter is less than 0.03 inches. Careful documentation of the variation of the capsule diameter along its length has allowed the selection of the most uniform capsules for the test runs. Capsule volumes are determined from the capsule weight in air and in water to an accuracy of 0.2% while the capsule weights are adjusted to the selected densities within 0.5%.

Data Acquisition

A PDP-8-S (Digital Equipment Corporation) mini-computer is used for acquisition and partial processing of the data and for control of the pipeline.

Figure 5 is a flow diagram showing how the measured variables enter the central processor, how the pipeline pumps and valves are controlled and how the data are recorded. The numbers near the top of the figure indicate how many channels are used to record each of the variables.

Temperatures are measured at the pipe inlet and outlet by two thermistors (Figure 1, T_i, T_o), each excited by a regulated 1.500 volt supply and providing D.C. voltages linearly related to the liquid temperatures. These voltages are converted to proportional frequencies which are then measured with binary counters by accumulating the frequency pulses for a selected period of time. The binary counters are interfaced to the central processor so that they can be read at any time, even when counting pulses. An overflow indicator in each counter interface permits the use of the central processor memory to expand the capacity of each counter.

Pressure differentials along the pipeline are measured between taps I and IV (see Figure I) with transducers of two ranges, one calibrated from 0 to 25 inches of water pressure differential and the other from 0 to 100 inches. The pressure taps in the pipe wall (Figure 6) are made by glueing C.A.B. blocks to the outside of the pipe and drilling these to provide 1/16 inch holes through the pipe wall. These holes are carefully deburred at the inner pipe wall and small vessels are attached to the blocks to remove entrapped air and to make pressure connections with the transducers. The D.C. voltages of the transducers, which are proportional to the pressure differentials imposed on them, are converted to frequencies and then read by counters in the same manner as described for the temperature measurements. In addition, the voltage from the high range transducer is displayed on an oscilloscope to allow monitoring of the pressure differential. Both transducers are used simultaneously and, since they cover different pressure ranges, allowed selection of the most accurate reading of the two after the data are collected.

A crystal oscillator and a counter, interfaced with the central processor, are used for recording time and photocells are used to detect the capsule train. As illustrated in Figure 7, laser beams passing through the clear pipe wall illuminate each photocell. When a laser beam is interrupted by the capsule train moving in the pipeline, the resulting electrical pulse from the photocell is recognized by the central processor via the photocell interface. Signals from the photocell interface are used by

the central processor in the data gathering program and in timing the control of the pipeline valves and pumps. They are also displayed on the oscilloscope superimposed on the trace of the pressure differential.

A 3-inch I.D. magnetic flowmeter is used for measuring liquid flow in the pipeline. This device, being insensitive to changes in liquid viscosity, generates an A.C. microvolt signal, which is converted to a frequency proportional to the liquid flow. The flow data were acquired in the same way as the temperature and pressure data.

The use of voltage to frequency converters connected to binary counters provides an effective method of data acquisition. Compared with a multiplexer and analog-to-digital converter, the voltage to frequency converters more readily allow accurately averaged signal measurements without congesting the input-output channel in a relatively slow mini-computer like the PDP-8-S.

Figure 8, which shows a typical trace of the pressure drop between the pipe taps as a capsule train moves through the pipeline, serves to illustrate the method. The fluctuating line represents the differential pressure between the two pressure taps in the pipeline and, since this is converted to a frequency in the data acquisition process, it also represents the analog frequency. In a typical pass capsules initially move in the pipeline towards the first pressure tap so that the pressure differential which is shown between B and C, is caused by the flowing liquid only - the liquid pressure drop. The trace of the pressure differential in the figure rises between C and D when the capsule train passes the first pressure tap, only to become approximately constant again when all the capsules have passed this tap. Consequently the trace shown between D and H represents the pressure differential as capsules move between the taps. While in this figure it is shown as being higher than the differential for the flowing liquid only, in practice it is sometimes lower for capsules with a density close to that of the liquid. It remains constant until the capsules reach the second pressure tap, after which it reverts to the pressure differential for liquid only.

In the data acquisition process, the liquid pressure differential is measured

by reading the counter at B, again reading it at C, and dividing the difference by the time interval measured as the capsules move between B and C. The resulting quotient represents the average liquid differential pressure measured as the capsule train moves between the photocells at B and C with flowing liquid only and no capsules between the pressure taps.

This may be expressed as:

$$\text{Average } \Delta P = \frac{\int_B^C \Delta P \, dt}{\int_B^C dt}$$

where ΔP is the instantaneous pressure differential between pressure taps and t is time. Similar integrations were also performed simultaneously for all the other variables, the time of integration in each case being the time of transit of the capsule train between the two consecutive photocells. By thus allowing the integration interval to vary, the lower range signals at the lower capsule velocities, which normally would have given lower accuracy levels, were improved in accuracy since they were averaged over a longer time period. The integrations are executed next as the capsule train passes between photocells D and E, and then between E and F, and then between F and H, thereby providing three average readings for all the variables but with the capsule train now moving between the pressure taps.

Computer Pipeline Controls

Pumps and valves in the pipeline are controlled from a register which is set by the computer, each of the valves and pumps being assigned to a specific bit in the control register. Setting of a particular register bit by the computer results in opening of the assigned valve or starting of the assigned pump while clearing of a particular bit has the opposite effect. The flow throttle valve is controlled by two bits in the same register so that one bit controls opening of the valve while the other bit controls its closing. This is necessary in order to adjust the control valve and then hold it at a selecting setting, the other valves being either fully open

or shut. The flow is controlled while the capsules are in the lock between valves 2 and 3 and by comparing the flow frequency measured by the computer with a pre-selected set point and then adjusting the throttle valve setting to give the selected flow. A table of 23 flow set points stored as part of the computer program provides for automatic selection of flow and pump setting for each sequential capsule pass during the test run. The flow settings for each run represent a range of descending liquid velocities in the pipeline from 8 to 0.2 ft./sec.

A typewritten copy, and a punched paper tape are produced after the data are partially processed by the PDP 8S computer. The punched tape is used for further processing and storing of data on a PDP 9 computer. The PDP 9 computer is used for correlating the collected data.

Instrument Calibration

The thermistors are calibrated by comparing the thermistor signals monitored by the counters with the temperatures of a water bath; all readings have been within 0.2% of the calibrations provided by the manufacturer.

The pressure transducers are calibrated by comparing the transducer signals with pressure differentials induced with two standpipes connected to the transducers. The calibrations are linear within $\pm$ 0.3% of range for each of the transducers but sequential calibrations vary within $\pm$ 0.5% of range per month due to drift of the instruments.

Calibrations of the flow meter are made by recording the transit time between photocells of a 0.95 diameter ratio PVC bobbin, provided with leather discs slightly larger than the pipe diameter, and comparing it with the signal from the flowmeter. Since the bobbin fills the entire cross-section of the pipe its velocity is exactly equal to the bulk liquid velocity. Various types of other devices such as pipeline spheres and rubber cup cylinders were tried initially for the calibrations but the bobbin was found to give the most consistent results. Variations between weekly calibrations of the flowmeter are in the order of 1% of range

while hourly variations are less than 0.5% of range. For this reason the calibrations are performed daily.

The transit timing system is checked periodically to make sure that the photocells and associated electronics respond to a change in light intensity within 500 microseconds. Since the distance between sequential light beams is accurate to within 0.02 inches, the accuracy of the capsule velocity measurement is within 0.2% at all velocities used.

The "as built" drawings are included and explained in Part 2 of the Phase I Report.

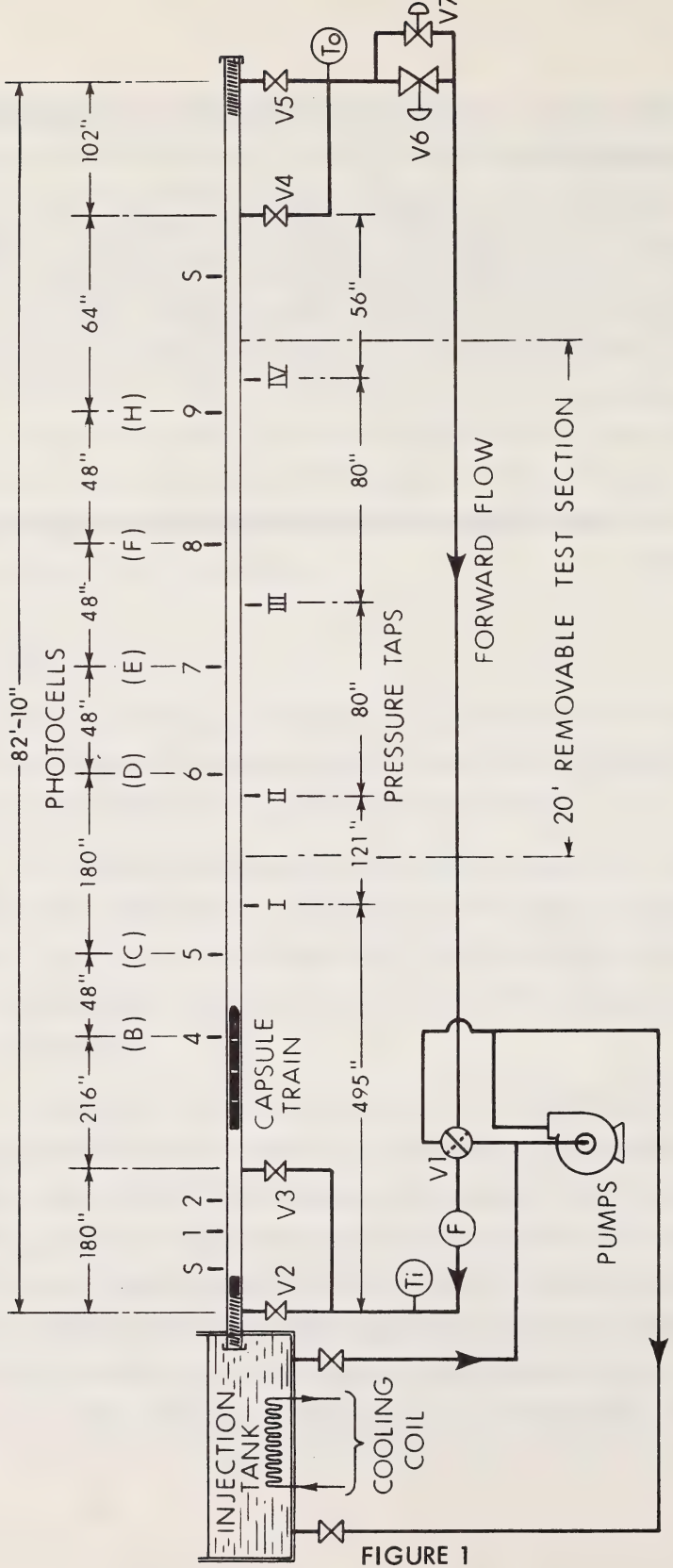


FIGURE 1

Schematic diagram of 4 inch pipeline

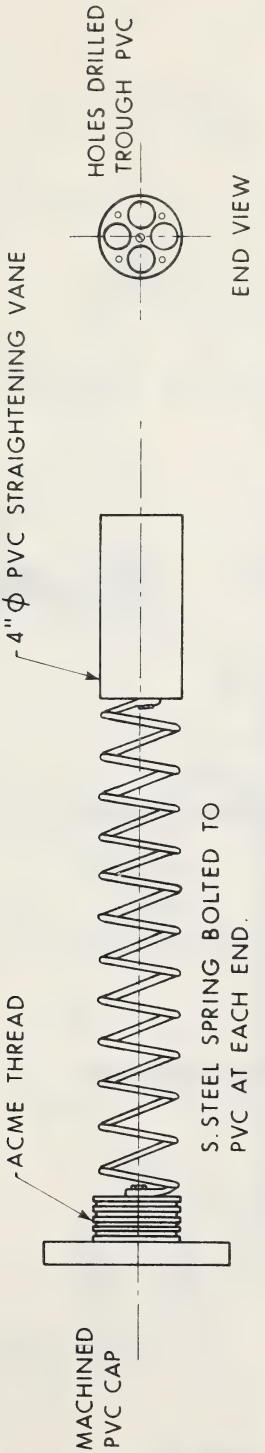

HOLES DRILLED TROUGH PVC
END VIEW
4" ϕ PVC STRAIGHTENING VANE
ACME THREAD
S. STEEL SPRING BOLTED TO PVC AT EACH END.
MACHINED PVC CAP

FIGURE 2

Spring and straightening vane

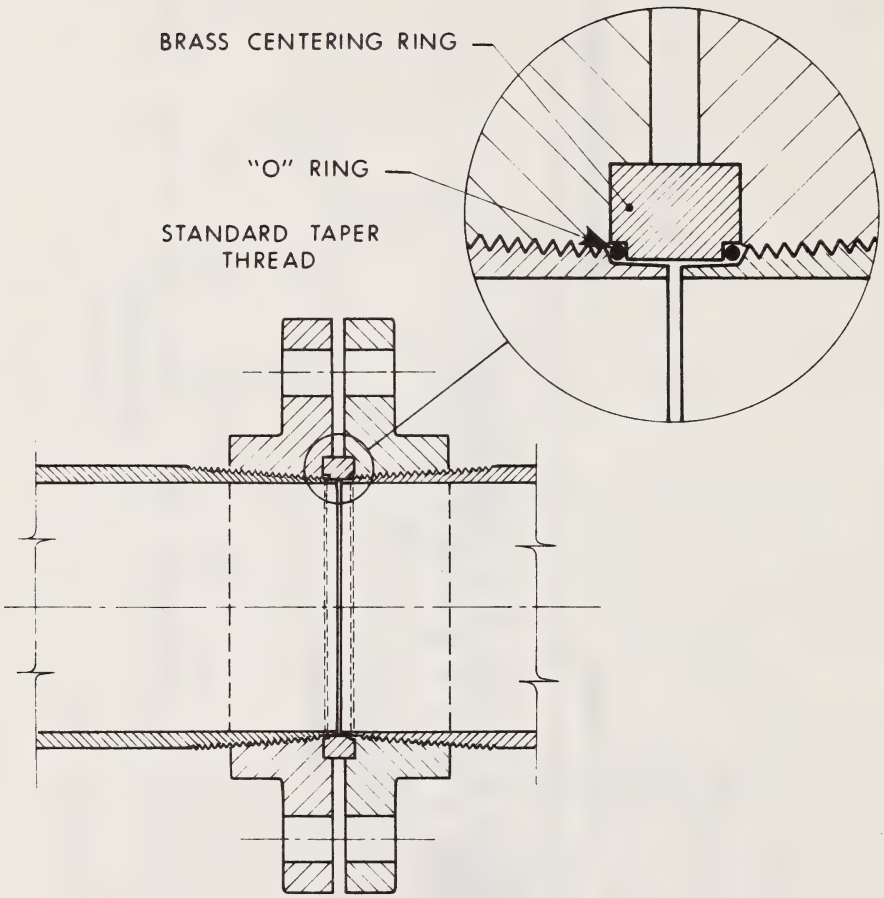


FIGURE 3

Flange connection, 4 inch pipeline

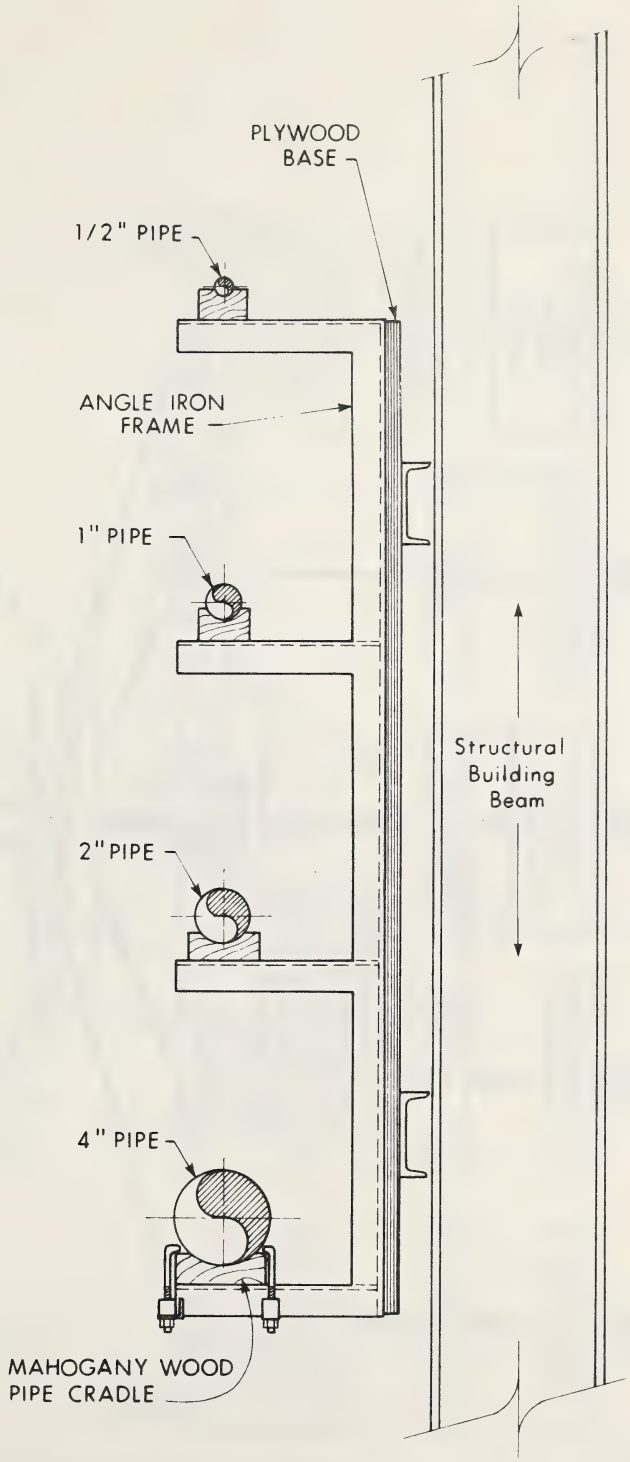


FIGURE 4

Pipeline support, 4 inch pipeline

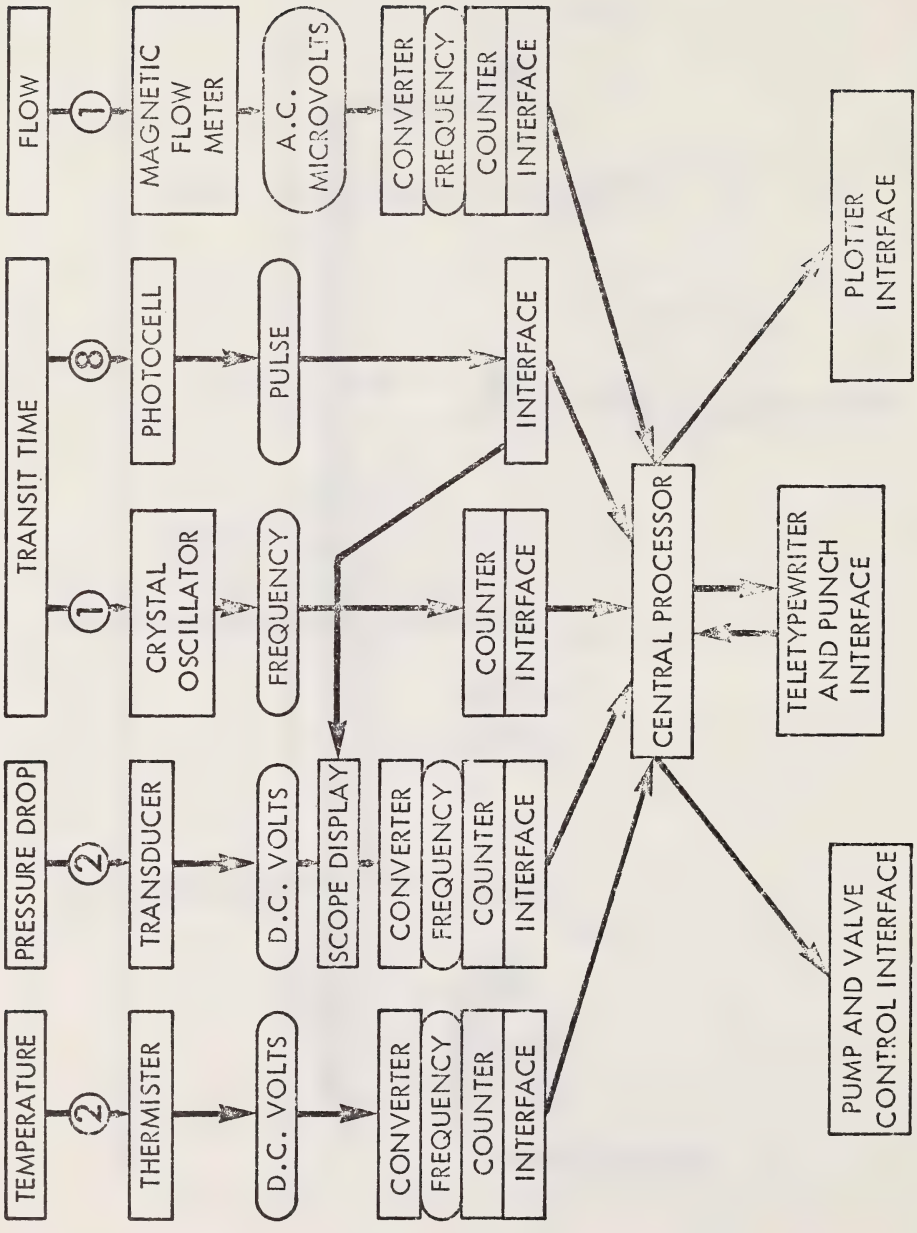


FIGURE 5

Flow diagram of the measured variables, 4 inch pipeline

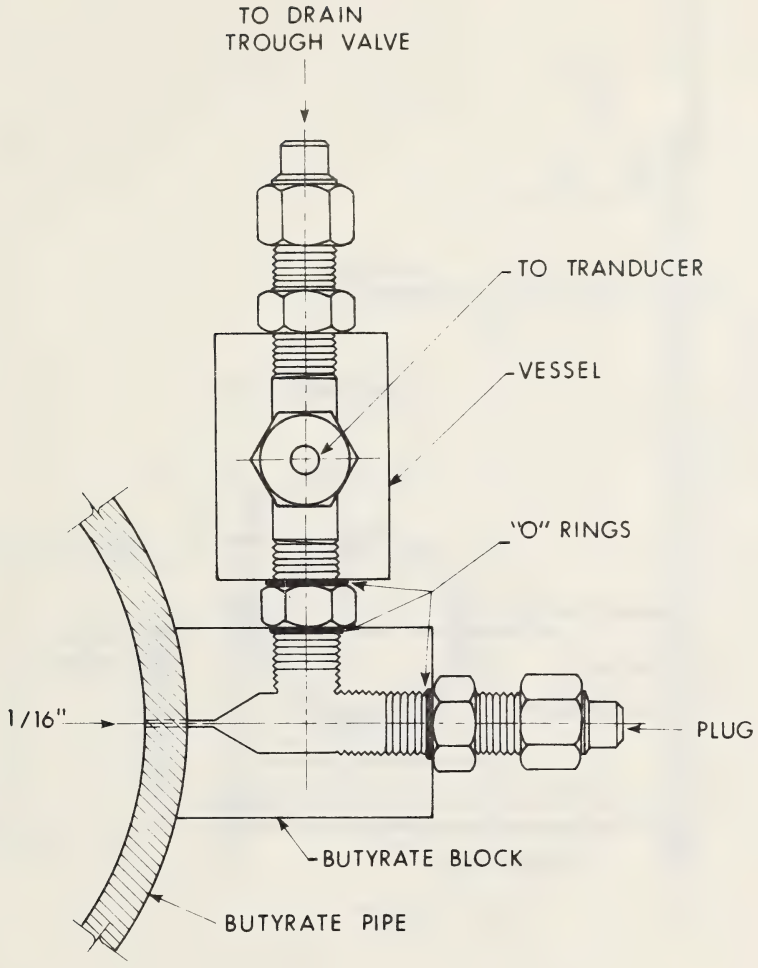


FIGURE 6

Pressure taps, 4 inch pipeline

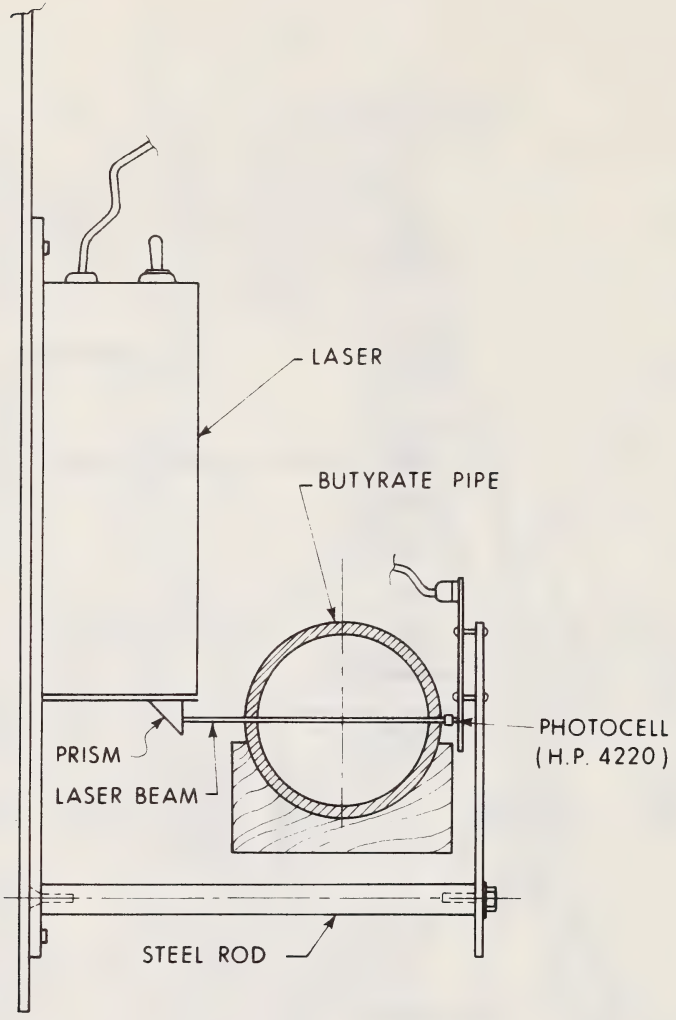


FIGURE 7

Photocell, Laser assembly, 4 inch pipeline

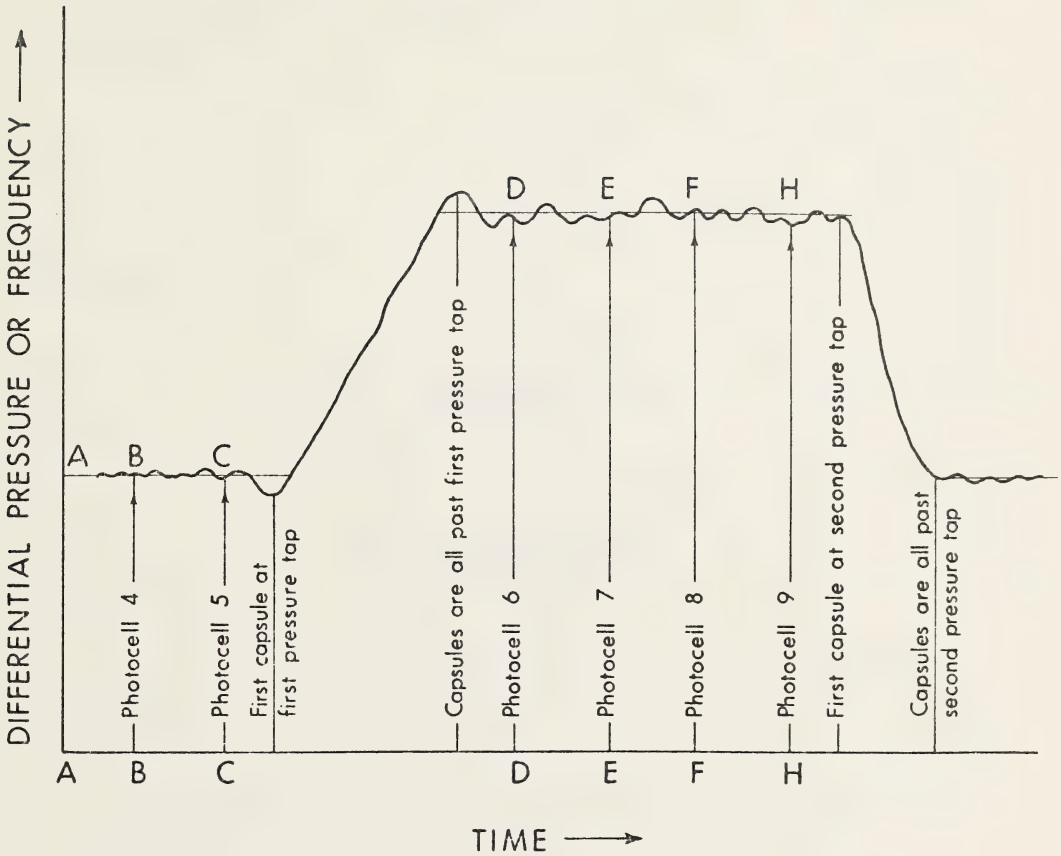


FIGURE 8

Typical trace of the pressure drop between two pressure taps as the capsule train flows past them, 4 inch pipeline

CHAPTER VII

Ten Inch Pipeline Facility

CHAPTER VII

Ten Inch Pipeline Facility

Location

To provide data for determining scale-up effects, a 10 inch diameter shuttle line, 400 feet long, has been designed and constructed.

The pipeline is located on a site made available by the City of Edmonton in southeast Edmonton. It is the same location used for the Solids Pipeline Research and Development Association project and already had a number of required facilities available. These existing facilities reduced the cost of the pilot facility considerably.

Another reason for selecting this site was the close proximity to a number of service industries and the convenient location with respect to the main laboratories of the Research Council of Alberta.

Design

A. General

The facility had to be long enough to permit steady state conditions to be attained before the basic parameters were measured, and also to provide enough pipe length for the capsule train to decelerate sufficiently to prevent collision with the end of the pipeline and to permit switching of the valves to reverse the flow. For further details, see sheets No. 1 and 2 in Appendix E.

The parameters measured are:

Liquid velocity
Capsule velocity
Liquid pressure gradient
Capsule pressure gradient
Temperature of the carrier liquid at a number of locations in the system.

The selection of water as the carrier liquid dictated that all piping and tankage had to be insulated and/or heated to permit all year operation at preset temperatures irrespective of climatic conditions.

A tunnel-like shelter, 4 1/2 feet wide, 4 feet high and 415 feet long was constructed from metal and insulated. The interior was heated with a propane fired thermostatically controlled furnace located approximately 200 feet from the main building. The heat was ducted along the entire tunnel and the air flow regulated with adjustable louvres.

The 10,000 gallon water tank was insulated with 2 inch semi-rigid insulation and covered with embossed aluminum sheathing. A 100,000 B.t.u.h. thermostatically controlled propane fired flue gas heater was installed near the bottom in the tank to provide sufficient heat to control the temperature of the carrier liquid.

All outside piping was traced with thermostatically controlled electric heating tape, insulated with 2 inch semi-rigid insulation and covered with aluminum sheathing.

The two 1,000 gallon propane tanks were equipped with 1000 watt "belly-band" vaporizers to ensure operation at temperatures as low as -30°F.

B. Building

The storage, office and control-room building is 40 feet long, 24 feet wide and 8 feet high at the wall. The building is constructed from 24 gauge galvanized steel on the outside, insulated and sheeted with 22 gauge aluminum on the inside. The entire structure is mounted on and fastened to a 4 inch thick steel reinforced concrete pad. The building is heated with a 122,000 B.t.u.h. propane fired furnace. (See sheets 3, 4 and 6 in Appendix E.)

C. Mechanical and Electrical

The wide range of operating velocities required dictate an arrangement that permits the use of several pumps, individually or in parallel. Three pumps were selected with one unit having a capacity of 300 USGPM at a head of 50 psi, another 600 USGPM at 50 psi, and a third 1200 USGPM at 50 psi. This permits the selection of velocity ranges with limited use of the control valve. (See Figure 1) With the use of the 6 inch fish-tail butterfly control valve any required liquid velocity between 0 feet per second and about 9 feet per second can be selected.

The output versus head for each pump and all combinations of the three pumps were measured, plotted and used in the design of the computer program to operate the facility. Details of pumps and motors are provided in Appendix A.

The nominal 10 inch main test line is 10.750 inches outside diameter with a 0.365 inch wall thickness. This pipe exceeds necessary pressure requirements, but since most valves and fittings are manufactured for standard pipe, it was expedient to avoid purchasing special line valves, fittings or making transition spools before and after each valve and fitting. Pipe lengths for the main test line were carefully checked and selected at the manufacturer's yard with specially prepared "go" - "no go" gauges, had the inside welds removed with a grinding wheel, and were assembled with modified socket-weld flanges. The flanges were selected in pairs to give matched inside diameters and fitted with three dowels at 120° spacing. The flanges were welded to the pipe with a "two-pass" weld and any part of the pipe not matching the flanges was removed with a grinder. The welding tended to shrink the pipe approximately 0.025 inches in the area of the weld. This, too, was removed to give a smooth pipe.

The pipe is supported on Grinnell pipe rolls mounted on 12 inch x 12 inch x 4 feet reinforced concrete blocks which are connected to and supported by 10 inch diameter, 8 feet long concrete friction piles. The supports and piles were constructed in a manner which permitted levelling of the line to within ± 0.01 feet.

The same precautions were not required for the return line, because no hydrodynamic parameters were measured in that part of the system, so the pipe lengths were joined with a "two-pass" weld. The return line is 8.625 inches outside diameter by 0.125 inch wall thickness.

For more details on the pipe and pumps see Appendix E, sheets 1, 2, 3, 4, 5, 6, 7 and 8.

The ends of the main test line and the return pipe are fitted with Huber-Yale scraper trap closures. This permits cleaning both lines with neoprene spheres and wire brushes. A 42 foot section of the 10 inch test line is bent in a vertical "S" bend to achieve a 3 foot elevation where it enters the main building for capsule injection and ejection.

The opening of the 10 inch pipe is at the same elevation as a 20 foot long roller conveyor fitted with a drip-pan which is connected to a 2 foot diameter by 10 foot long return tank. During ejection the capsules move along the conveyor, the water spills into the return tank and is returned to the main reservoir with a centrifugal pump. The liquid level in the return tank is controlled with a level-control float switch.

Prior to injection the capsules are loaded on the conveyor with an electric operated fork lift, then moved along the conveyor and pushed into the open end of the test pipe.

When all capsules required for a test are injected, the scraper trap closure is put into place, the line is vented to remove air and the train is ready for the test runs desired.

The cylindrical capsules are constructed from seamless mechanical tubing which is cut to 4 foot lengths and the ends fitted with 1.5 inch PVC end caps and O-ring seals. The capsules are 8.5 inches, 9.0 inches and 9.5 inches in diameter. The removable end caps permit opening of the cylinders so that

steel rods can be inserted or removed to weight the capsules to the required densities. Provision has also been made to modify the cylinders for bands and a number have been prepared with various surface roughnesses.

In addition two densities of spheres, cast aluminum and cast iron, with the same diameters as the cylinders have been prepared.

D. Control Instrumentation

All valves not requiring frequent or rapid operation are manually operated. The flow control valve, diverter valve, system by-pass valve (Appendix E, sheet 7) and capsule collection valves CCV_1 and CCV_2 (Figure 1) are pneumatically operated. To make the pneumatic operation compatible with computerization, electrically operated solenoid valves are used for the "open/closed" operation and a Fisher 546 current/pneumatic transducer is used on the 6 inch Fisher Continental butterfly flow control valve which requires infinite resolution between and including fully open and fully closed positions. The current to the pneumatic transducer is connected to a Fisher No. 3580 positioner which in turn operates a Fisher No. 40 actuator. This permits rapid valve operation, repeatable positioning of the valve positioner, and holding of a particular flow setting.

The pump discharge pressures are piped to the control panel and connected to 3 inch Marshalltown bourdon tube gauges.

The operator's control console is designed and constructed to provide ready access to operate all equipment. It also contains visual analog outputs on meters of all equipment requiring monitoring throughout the system. This includes flow control valve setting, liquid flow rates, temperature of the main tank, four temperatures along the pipeline, three temperatures inside the pipeline enclosure, pressure transducer performance, photo detector operations and power supply outputs.

The upper part of the console has a schematic diagram of the facility

with lights indicating the location of the capsule trains as well as the operation of the light sources (Metrologic Model 420 helium-neon lasers) and photo detectors (Fairchild FPT 100 NPN planar photo transistors). For more details see Appendix E, sheet No. 5, and Figure 1.

For indication purposes meters were sufficiently accurate, but for data taking or for accurate measurements ±2% is not accurate enough and a model 5223L Hewlett Packard counter has been installed to measure the output of all primary data measuring devices.

All devices can be connected to the Hewlett Packard counter through a rotary selector switch and a Dymec model 2210 voltage to frequency converter. This permits checking transducer outputs to ±0.1%, during calibration, or for performance when in operation.

E. Data Acquisition

The liquid flow is measured with a 6 inch model 1806-KAOS-RA Foxboro magnetic flow transmitter which is connected to a Foxboro model 696A flow-to-current converter with a 4 step externally switched range selector. The accuracy of this system is rated at ±1% of full scale with a repeatability of ±0.25% of full scale. With careful calibration it has been found that results can be obtained to within 0.1% of range.

The liquid pressure gradients are measured with a Foxboro model E13DL differential pressure transducer which is calibrated to a range of 0-5 inches of water. The accuracy of this instrument is rated at ±0.5% of full range. A manometer system which can be read to 1/20 inch of water is used for calibration.

The capsule pressure gradients are measured with a Honeywell model NDI-22-1, 0-50 inches of water differential pressure transducer which has an accuracy of ±0.5% of range, and is calibrated in the same way as the transducer used to measure the liquid gradient.

Temperatures in the storage tank, at the entry to the 10 inch test line, before the entry to the test section, at the end of the test section and the end of the test line, are measured with YSI-44203 thermistor-resistor networks which are calibrated to ±0.2 degrees Fahrenheit with a calibrated standard laboratory themometer. The analog outputs of the pressure and temperature transducers are amplified where required and through suitable interfacing made compatible with a multiplexer constructed from Digital Equipment of Canada A121 switches included in a Type AFOI Analog-to-Digital Converter. The digitized signal is then fed to a Digital Equipment of Canada PDP 8/S central processor with a 4,096 word core memory.

For details of the electronic interfacing to the computer see sheets 9, 10, 11, 12, 13, 14, 15 and 16 in Appendix E.

The capsule velocity is measured when the train passes through a number of successive light beams trained across the pipeline (Figure 1). The light sources are Metrologic Model 420 helium-neon lasers which have a 2.0 milliwatt to 4.0 milliwatt output. The photo sensitive detectors opposite the laser beams are Fairchild FPT 100 phototransistors. As long as the light source is on and a narrow 1/8 inch diameter beam focussed on the detector, the phototransistor is conducting, resulting in a network output of +15 volts. When the light beam is discontinued the transistor does not conduct and the resultant network output then is -15 volts. The output from the detectors is fed to the computer and when the photo detector senses an interrupt in the light beam the computer then performs the function or functions programmed. In the case of capsule timings, the first signal requires that the computer reads a D.E.C. KWO8S-5000 cycles/sec. crystal oscillator clock. As the train passes the next photocell detector, the clock is read a second time and the time interval calculated. The distances between the photocells have been measured carefully and the dimensions programmed into the computer. After the second clock reading the computer calculates the velocity of the lead capsule in the capsule train.

At photocell 3 (PC_3) the program is expanded to permit the computer to calculate the spacing, if any, between capsules in the train.

The software program is written so that the computer is able to translate the analog signals into engineering terms and print these out on paper (Figure 2), punch the data on paper tape and plot the data on an 11 inch x 17 inch graph (Figure 3) with a Hewlett Packard Model 7004B X-Y recorder.

The computer is also programmed to control the liquid velocity, select the correct pumps and flow meter range, reverse the liquid and train and indicate when it is ready for a new instruction. Since this is a prototype project it has been difficult to anticipate the data results, and provision therefore has been made for the operator to decide if the data obtained are valid and if not, to reject them so that the best obtainable data are used for analysis. The criteria for valid data are that fluid and capsule velocities are stable, that the train is not spread out and that all systems are functioning. If these conditions are met, the data are accepted whether they agree with previous values or not, and the next velocity is selected; when there is an apparent discrepancy in the parameters measured, the pass is repeated before the data are accepted. This procedure requires that the operator is alert to the equipment operation and makes prescribed systematic checks.

System Calibration

The selection of components, the care with which they are installed, and the method of operation of these determine the system accuracy and precision.

The selection of the various components, the methods used to calibrate them and their inherent accuracies and tolerances are discussed in the main text and in Appendices A, B, C and E.

The analog to digital converter used in the computer, a primary component in converting data from analog signals to their final form in engineering terms, was calibrated to an accuracy of 1.22 millivolts absolute over the 0 to -10 volt range or $\pm 1/2$ least significant bit.

The AFOI Digital Equipment Corporation analog to digital converter was calibrated with a No. 885 John Fluke precision differential voltmeter and a No. 865C Harrison Laboratories regulated power supply. These were made available to the project by the Primary Calibration Laboratory of the Northern Alberta Institute of Technology.

When all instruments used for obtaining data were calibrated, a Moody diagram was then run and plotted to test the calibrations. The results were compared with theoretical data and previous runs. When consistency in the Moody diagram plots was achieved as well as good comparison with theoretical values, then the system was considered to be calibrated and the experimental program begun. Systematic checks and re-calibrations are performed as required by the experimental program.

Appendix C describes in detail how the results from the mechanical calibrations were used in the computer program.

System Operation

To inject the capsules, the scraper trap on the 10 inch line is vented, opened, and excess liquid allowed to drain into the return tank. The capsules are then pushed into the open line. When all capsules are inserted, the scraper trap is closed, the air vented and the train is ready for the test run or runs planned.

A new chart is put on the plotter, calibrated and new capsule parameters are teletyped into the computer memory, printed on paper and punched on paper tape to identify the run. When these instructions and the date are properly recorded the operator selects the velocity with which he wishes to start, and also indicates the increments he wishes the computer to use for the succeeding passes. This can be changed any time after a particular pass is completed.

As soon as the desired starting velocity and increments are typed in on the teletype the computer is ready to execute the commands. A pass through the

test section is initiated when the appropriate command is entered on the teletype (see Appendix C). The computer selects the right pump or pump combination, valve CCV_2 (capsule control valve; see Figure 1) is opened and the preset flow rate is established with a direct digital control loop. The valve opening is compared with the flow meter output and the valve opening adjusted in increments till the required flow rate is attained. The flow valve opening is then "locked" to prevent change, and valve CCV_1 opens while CCV_2 closes. The liquid now enters behind the capsule train, moving it forward in the pipeline.

When the train passes PC_o (photocell) all registers and flip-flops in the computer are cleared and the level lights on the control panel switched off.

Ten seconds after CCV_1 is opened the computer opens the isolation valves (S_1 and S_2; S_4 and S_5) and closes the bypass valves (S_3 and S_6) to the pressure transducers and thus put them on line (see Figure 1). This prevents excessive mechanical shock to the transducers.

As the train moves through the pipeline it passes PC_1 which functions as an indicator of the train movement only. During this time the computer scans the pressure transducer outputs. If the liquid gradient on the high range cell is greater than 4.5 inches of water, it will read only the high range (Honeywell) cell. If the pressure is less than 4.5 inches of water it will read the low range cell when the train arrives at PC_2.

When PC_2 signals the presence of the capsule train the computer reads the 5 KHZ clock and also reads the flow meter output, the output from the selected pressure transducer, as well as the temperatures along the test line T_1, T_2, T_3, T_4, and then awaits a signal from PC_3. When the signal from PC_3 is received the computer again reads its internal 5 KHZ clock and continues to read it every time a signal or interrupt is received from the photocell as the train passes.

After the train has passed PC_3 the computer calculates the liquid velocity at PC_2, the capsule velocity between PC_2 and PC_3, the liquid pressure

gradient over the test section, temperatures T_1 - T_4 and the spacings between the capsules, if any. When these operations are completed and the low range Foxboro cell isolated by closing S_4 and S_5 and opening the bypass S_6, the data are transferred to core storage and an interrupt from PC_4 awaited. After the PC_4 interrupt the computer again reads the clock and, since the distance and elapsed time interval between PC_3 and PC_4 are known, calculates the velocity of the lead capsule in the train. As soon as this is completed the values are put into core storage and a signal from PC_5 awaited. When the interrupt from PC_5 is received the clock is read again and the train velocity between PC_4 and PC_5 calculated. This ensures that a stable capsule velocity is reached before data used for interpretation are taken. When the train reaches PC_6 the clock, the liquid flow, the high range (Honeywell) transducer, and all temperatures are read, and the high range transducer isolated by closing S_1 and S_2 and opening the bypass S_3. When the train reaches PC_7, the clock is read the sixth time. The flow control valve is closed, the system bypass valve opened, the diverter valve switched to the return position, valves CCV_1 and CCV_2 opened, and the mechanical part of the system shut down while the computer calculates the velocity between PC_5 and PC_6, the liquid velocity, the capsule pressure gradient, all temperatures and the velocity of the train between PC_6 and PC_7. When all computations have been made, the following parameters are printed on the teletype: (Figure 2)

Liquid velocity at PC_6

Liquid pressure gradient - when the train is at PC_2

Capsule velocity between PC_6 and PC_7

Capsule pressure gradient

Temperatures T_1, T_2, T_3, T_4

Spacing, if any, between capsules

Velocities between PC_2 - PC_3; PC_3 - PC_4; PC_4 - PC_5 - PC_6; and PC_6 - PC_7

Liquid velocity while train at PC_2

When the above has been typed out the train is returned at velocities between 3.5 and 4.0 feet per second.

While the train is returning to the starting end of the line the operator examines the data to assure that the liquid velocities at PC_2 and PC_6 do not differ by more than 1%, that the train hasn't spread, or a major variation in temperatures 1 to 4 has not occurred, and also that the capsule train achieved uniform velocity before reaching PC_6. If all these conditions are met, the data are considered valid and are accepted; if not, a repeat pass is indicated or all instruments have to be checked.

Thirty seconds after the train returns to PC_0 the flow valve is closed, CCV_1 and CCV_2 are closed, the system bypass valve opened and the diverter valve switched to the forward position. The system bypass valve is closed, and the mechanical part of the system assumes a waiting mode.

During the waiting mode the operator teletypes acceptance of the data. The data are again typed out, identified as accepted, punched on paper tape and plotted on the graph. (Figure 4) When the plot is completed the operator instructs the computer to initiate another pass at a new preset velocity. If the data are not acceptable, the operator instructs the computer to repeat the pass. The initial data are then removed from core storage. A run consists of 16 to 23 passes at velocity increments of approximately 1/2 ft./sec. The data from a completed run are then checked and delivered for further processing, evaluation and correlation.

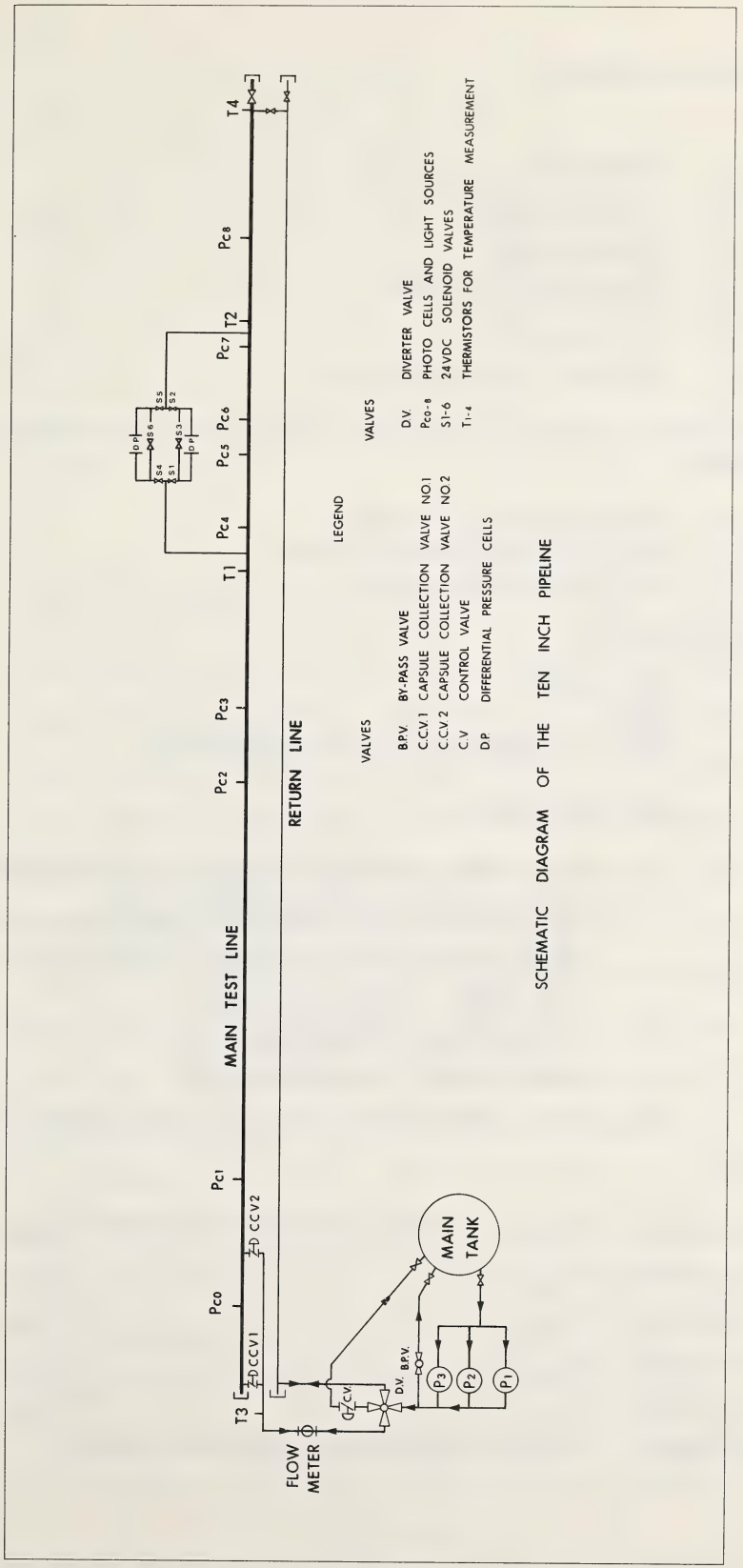

SCHEMATIC DIAGRAM OF THE TEN INCH PIPELINE
LEGEND
VALVES
B.P.V. BY-PASS VALVE
C.C.V.1 CAPSULE COLLECTION VALVE NO.1
C.C.V.2 CAPSULE COLLECTION VALVE NO.2
C.V CONTROL VALVE
D.P. DIFFERENTIAL PRESSURE CELLS
VALVES
D.V. DIVERTER VALVE
Pc0-8 PHOTO CELLS AND LIGHT SOURCES
S1-6 24VDC SOLENOID VALVES
T1-4 THERMISTORS FOR TEMPERATURE MEASUREMENT
MAIN TEST LINE
RETURN LINE
MAIN TANK
FLOW METER
T1
T2
T3
T4
Pc0
Pc1
Pc2
Pc3
Pc4
Pc5
Pc6
Pc7
Pc8
CCV1
CCV2
C.V.
D.V.
B.P.V.
P1
P2
P3
S1
S2
S3
S4
S5
S6
D P I

FIGURE 1

EXPLANATION TO FIGURE 2

)CT - Capsule Type
)RO - Capsule Roughness
)CD - Capsule Diameter
)CL - Capsule Length
)CG - Capsule Specific Gravity
)NC - Number of Capsules
)TL - Train Length
)PI - Pipe Index (test section type)

For further information on the above, see right hand side of graph of Figures 3 and 4.

)TR - Temperature Range for Graph
)PR - Pressure Gradient Range for Graph
)ST - Starting symbol for computer

Run Information:

Run: number
Date
G & C - prefixing each line of accepted data.

From left to right:-

first number is velocity of liquid at PC6 (see Figure 1)
second number is pressure gradient of liquid
third number is velocity of leading capsule between PC6 and PC7
fourth number is pressure gradient of capsule train
fifth number - Temperature 1 (T1)
sixth number - Temperature 2 (T2)
seventh number - Temperature 3 (T3)
eighth number - Temperature 4 (T4)

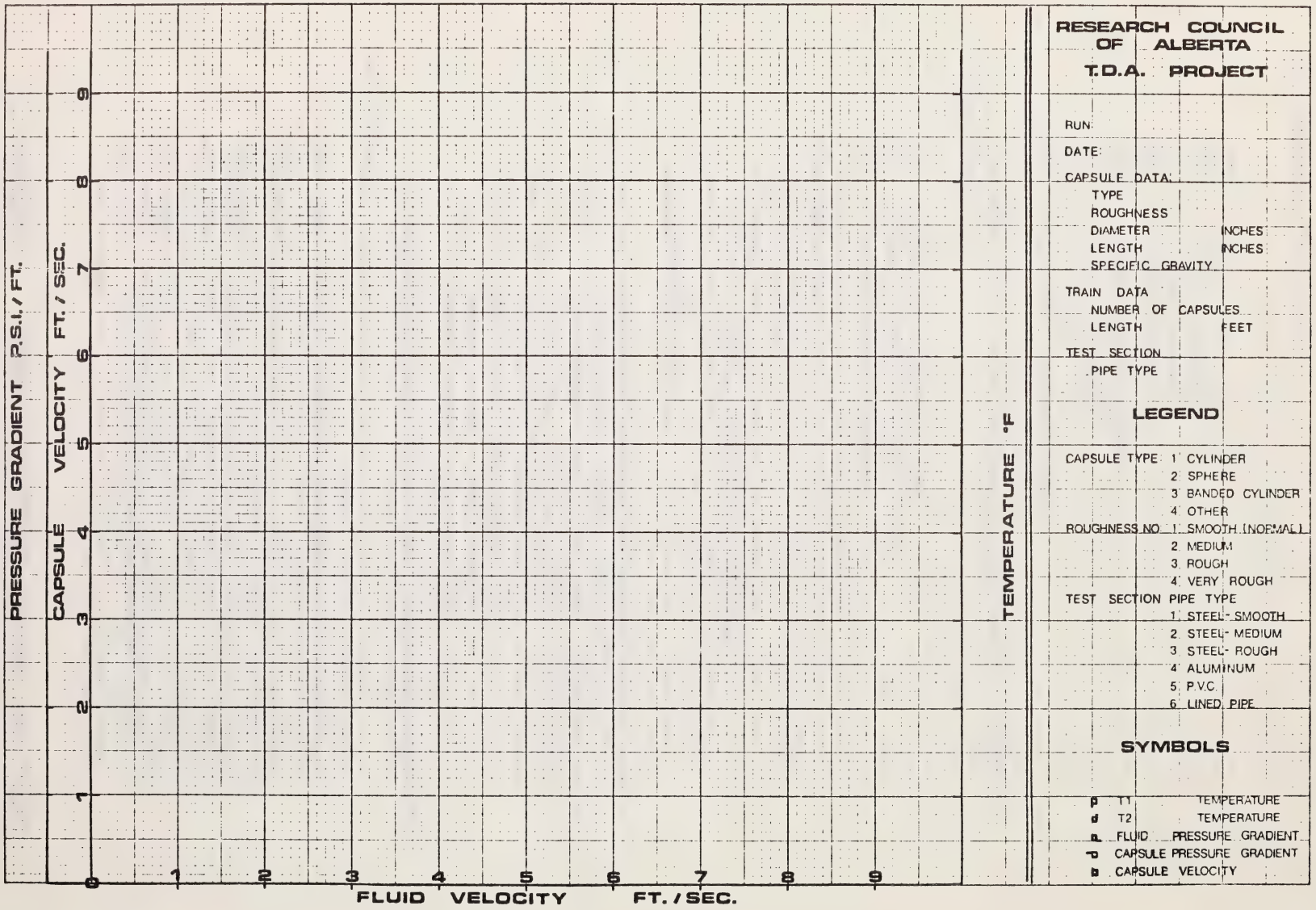
The last four numbers of first column are capsule spacings at PC3.

Second Line:

1st number - VC_{2-3} - Velocity of capsule train between PC_{2-3}.
2nd number - VC_{3-4} - " " " " PC_{3-4}.
3rd number - VC_{4-5} - " " " " PC_{4-5}.
4th number - VC_{5-6} - " " " " PC_{5-6}.
5th number - VC_{6-7} - " " " " PC_{6-7}.
6th number - Velocity of liquid while capsule train is at PC_2.

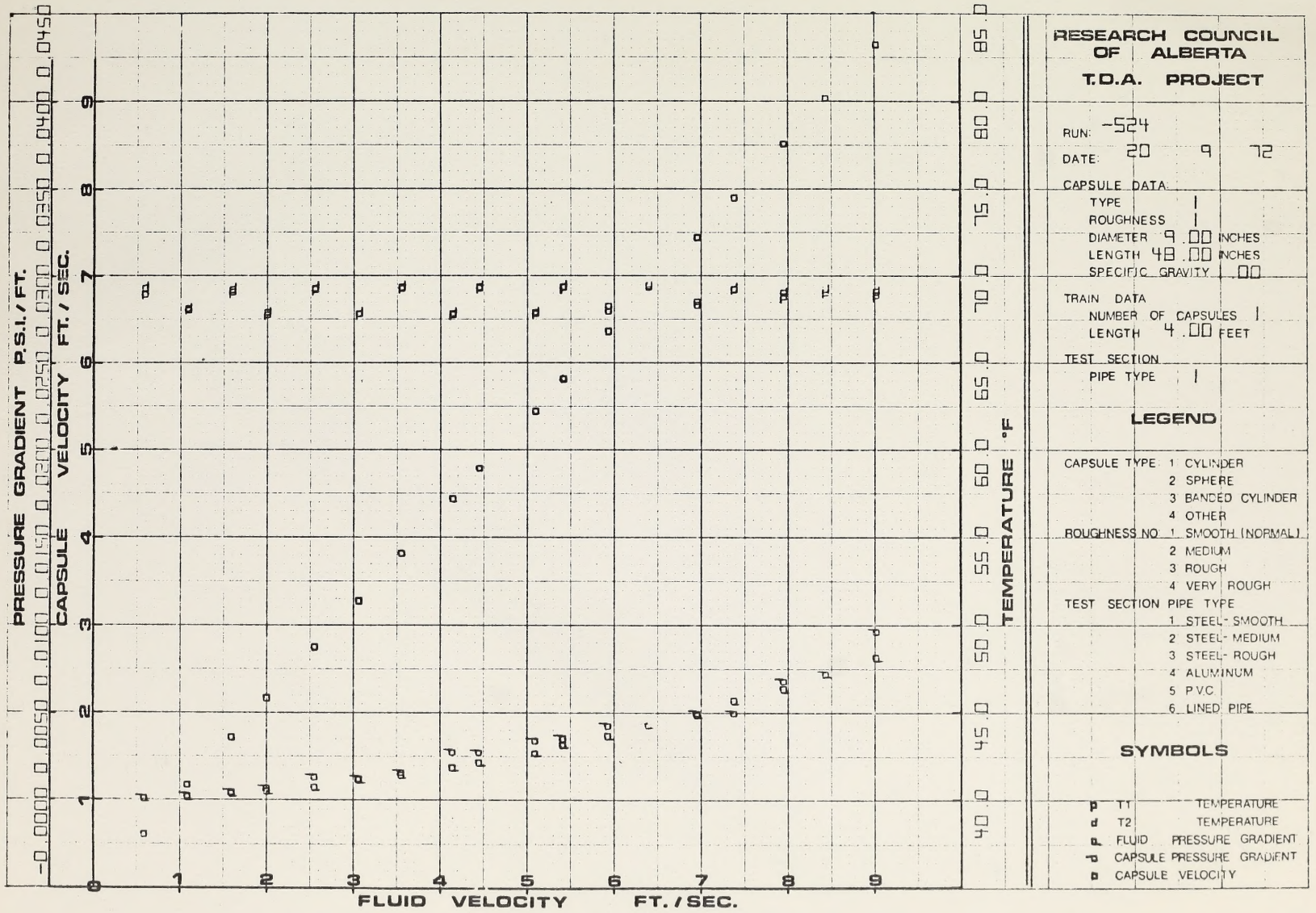
```
)CT
1

)K0
1

)CD
9.0

)CL
48.0

)CG
1.00

)NC
1

)TL
4.0

)PI
1

)TR
35 85

)PR
-.005 .045

)ST


RUN::  -524.

DATE:: D M Y   20 9 72
G 1.083 0.00017 1.167 0.00019 68.1 68.0 67.0 68.0 0.00 0.00 0.00 0.00
C 1.16 1.16 1.17 1.16 1.17   1.078

G 2.004 0.00052 2.164 0.00067 67.7 67.8 67.1 68.0 0.00 0.00 0.00 0.00
C 2.16 2.16 2.16 2.15 2.16   2.006

G 3.062 0.00114 3.276 0.00122 67.8 67.8 67.2 68.1 0.00 0.00 0.00 0.00
C 3.25 3.26 3.27 3.26 3.28   3.036

G 4.146 0.00188 4.431 0.00272 67.7 67.8 67.2 68.0 0.00 0.00 0.00 0.00
C 4.41 4.41 4.43 4.42 4.43   4.099

G 5.102 0.00262 5.442 0.00335 67.8 67.8 67.2 67.9 0.00 0.00 0.00 0.00
C 5.41 5.45 5.45 5.44 5.44   5.053

G 5.942 0.00361 6.357 0.00422 68.2 67.9 67.4 67.9 0.00 0.00 0.00 0.00
C 6.39 6.36 6.35 6.33 6.36   5.939

G 6.969 0.00485 7.438 0.00493 68.5 68.3 67.4 68.3 0.00 0.00 0.00 0.00
C 7.46 7.45 7.48 7.44 7.44   6.967

G 7.966 0.00629 8.517 0.00670 68.8 69.0 67.7 69.0 0.00 0.00 0.00 0.00
C 8.47 8.49 8.53 8.50 8.52   7.920

G 9.048 0.00809 9.651 0.00959 68.8 69.1 67.7 69.0 0.00 0.00 0.00 0.00
C 9.67 9.66 9.66 9.62 9.65   9.028

G 8.459 0.00715 9.046 0.00717 69.0 69.2 67.8 69.1 0.00 0.00 0.00 0.00
C 9.01 9.03 9.02 9.02 9.05   8.468

G 7.395 0.00564 7.901 0.00492 69.2 69.2 68.0 69.0 0.00 0.00 0.00 0.00
C 7.94 7.92 7.94 7.91 7.90   7.395

G 6.414 0.00432 6.868 0.00419 69.5 69.4 68.3 69.4 0.00 0.00 0.00 0.00
C 6.90 6.90 6.87 6.84 6.87   6.411

G 5.427 0.00312 5.811 0.00347 69.3 69.4 68.1 69.3 0.00 0.00 0.00 0.00
C 5.80 5.81 5.81 5.80 5.81   5.435

G 4.462 0.00216 4.782 0.00272 69.3 69.4 68.3 69.3 0.00 0.00 0.00 0.00
C 4.74 4.76 4.77 4.76 4.78   4.418

G 3.557 0.00144 3.820 0.00158 69.3 69.4 68.5 69.4 0.00 0.00 0.00 0.00
C 3.80 3.82 3.81 3.81 3.82   3.558

G 2.556 0.00075 2.737 0.00128 69.2 69.3 68.6 69.5 0.00 0.00 0.00 0.00
C 2.73 2.74 2.74 2.73 2.74   2.549

G 1.594 0.00032 1.711 0.00041 69.0 69.2 68.5 69.6 0.00 0.00 0.00 0.00
C 1.71 1.71 1.71 1.70 1.71   1.586

G 0.584 0.00004 0.621 0.00006 68.9 69.3 68.9 69.8 0.00 0.00 0.00 0.00
C 0.62 0.62 0.62 0.62 0.62   0.575
```

TELETYPE "PRINT-OUT" OF A RUN FIGURE 2



PRE-PRINTED GRAPH PAPER

FIGURE 3



COMPUTER PLOT OF A RUN

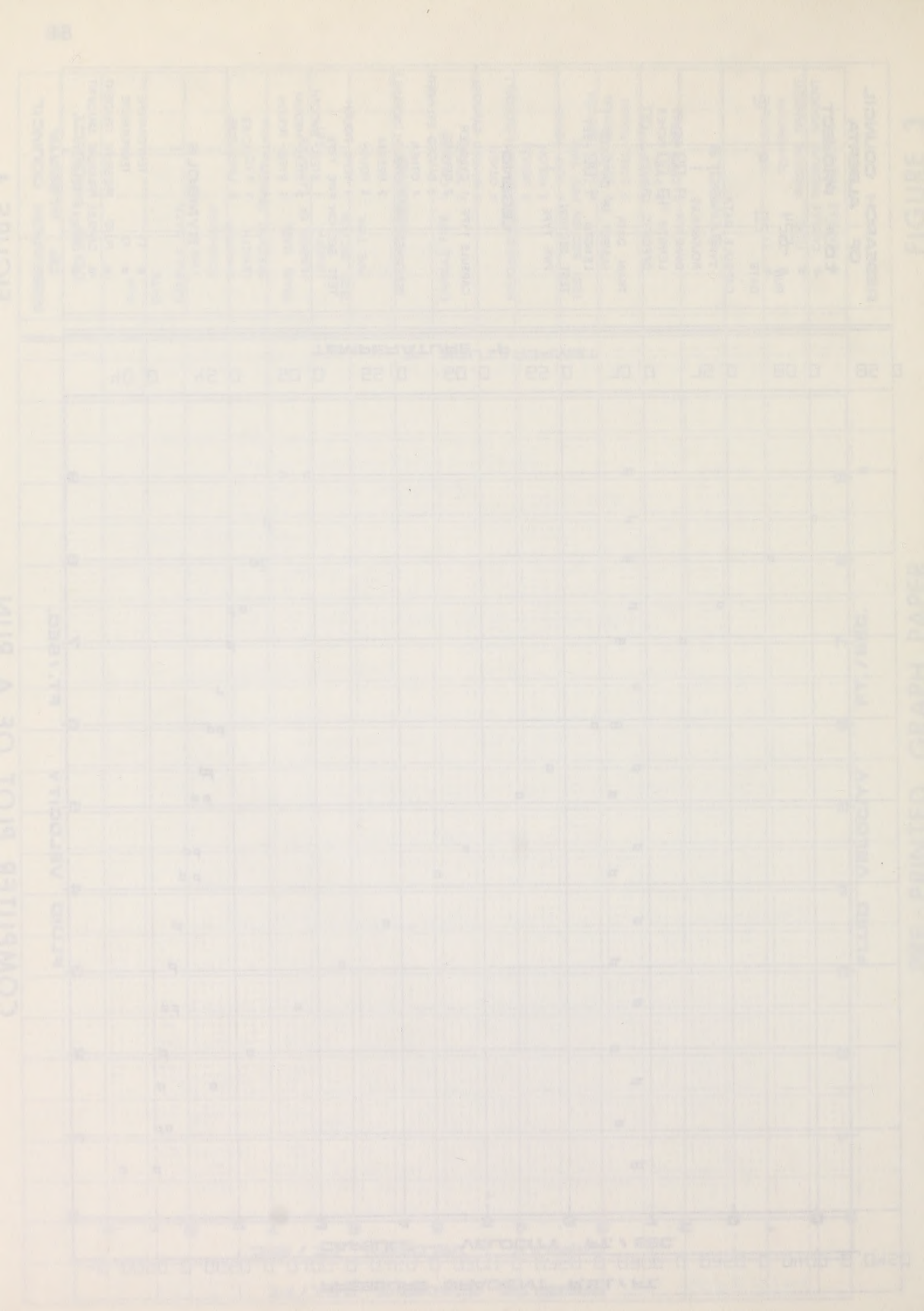



FIGURE 4